On the use of WiMAX and Wi-Fi in a VANET to Provide in-Vehicle Connectivity and Media Distribution

By

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Declaration

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Date: December 2011

Abstract

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The recent emergence of ubiquitous wireless connectivity and the increasing computational capacity of modern vehicles have triggered immense interest in the possibilities of vehicular connectivity. A plethora of potential applications for vehicular networks have been proposed in the areas of safety, traffic infrastructure management, information, and entertainment. The broad range of applications requires creative utilisation of the available wireless medium, using a combination of existing and novel wireless technologies. In this research the evaluation of one such configuration is performed. Dedicated short range communication for safety applications is assumed, and the use of Wi-Fi and WiMAX for non-safety applications is evaluated. Little is known about the media streaming performance of these wireless technologies in realistic vehicular ad-hoc network (VANET) scenarios. Due to the extreme mobility and unpredictable environmental aspects in a real road environment, an empirical evaluation is performed and presented. Evaluation of a multi-vehicle to infrastructure (V2V2I) VANET, using Wi-Fi for the vehicle-to-vehicle communication and WiMAX for the vehicle to infrastructure (V2I) communication is experimented. It is observed that Wi-Fi is unaffected by the vehicle speed; whenever nodes are within communication range, data gets transferred normally. A detailed characterisation of the network architecture is presented and the results show that a multitude of applications can be supported with this proposed network architecture.

Samevatting

Die Gebruik van WiMAX en Wi-Fi vir Netwerkkommunikasie en Mediaverspreiding in 'n VANET

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Die toenemende beskikbaarheid en digtheid van koordlose netwerke en die verhoogde verwerkingsvermoëns van moderne voertuie het die afgelope paar jaar aansienlike belangstelling gewek in die moontlikhede wat voertuig-kommunikasie bied. ŉ Magdom moontlike toepassings is voorgestel in ŉ wye verskeidenheid van velde insluitende veiligheid, verkeersinfrastruktuur, informasie en vermaak. Hierdie voorstelle vereis die kreatiewe benutting van die beskikbare en nuwe koordlose tegnologieë. Hierdie tesis evalueer een voorbeeld van so 'n opstelling. ŉ Toegewyde kortafstand kommunikasie modus vir veiligheidstoepassings word aangeneem, terwyl Wi-Fi en WiMAX vir ander toepassings evalueer word. Daar is min navorsing oor die kapasiteit en seinsterkte van hierdie beskikbare netwerke onder realistiese voertuig netwerk (VANET) scenario's. Weens die hoë mobiliteit van voertuie en ook die onvoorspelbaarheid van hierdie omgewing word ŉ empiriese evaluasie beskou as die mees gepaste metode. Die navorsing ondersoek ŉ multi-voertuig-tot-infrastruktuur-netwerk wat Wi-Fi gebruik vir voertuig-tot-voertuig (V2V) kommunikasie en WiMAX vir voertuig-tot-infrastruktuur (V2I) kommunikasie. Die navorsing bevind dat Wi-Fi nie beïnvloed word deur die spoed van die voertuig nie: wanneer die nodes binne die bereik is van die netwerk word data normaal oorgedra. ‘n Gedetailleerde karakterisering van dié netwerk word gedoen en die resultate dui aan dat ‘n groot hoeveelheid toepassings ondersteun kan word deur dié opstelling.

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I would like to pass my sincere regards to the following:

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Dedications

To my family who have urged, encouraged and supported me to continue with my studies.

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List of Abbreviations

AODV	Ad hoc On-demand Distance Vector
AU	Application Unit
BMMM	Batch Mode Multicast MAC
BMW	Broadcast Medium Window
BPSK	Binary Phase Shift Keying
C2C CC	Car-to-Car Communication Consortium
CAR	Connectivity Aware Routing
CCK	Complementary-Code Keying
COIN	Clustering for Open IVC Network
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DCF	Distributed Coordination Function
DREAM	Distance Routing Effect Algorithm for Mobility
DSDV	Destination-Sequenced Distance-Vector
DSR	Dynamic Source Routing
DSRC	Dedicated Short-Range Communication
DSSS	Direct Sequence Spread Spectrum
EDGE	Enhanced Data rates for Global Evolution
ETSI	European Telecommunications Standards Institute
FHSS	Frequency Hopping Spread Spectrum
GPRS	General Packet Radio Service
GPSR	Greedy Perimeter Stateless Routing
GSM	Global System for Mobile communications
HIPERLAN	High Performance Radio LAN
HSPA	High Speed Packet Access
HWN	Heterogeneous Wireless Network
IEEE	Institute of Electrical and Electronics Engineers
ITS	Intelligent Transportation Systems
LAN	Local Area Networks
LLC	Logical Link Control layer
LTE	Long Term Evolution
MAC	Media Access Control

MAN	Metropolitan Area Network
MANET	Mobile Ad hoc Network
MIMO	Multiple-Input Multiple-Output
MLME	MAC Layer Management Entity
NAV	Network Allocation Vector
OBU	On Board Unit
OFDM	Orthogonal Frequency Division Multiplexing
PCF	Point Coordination Function
PDA	Personal Digital Assistant
PHY	PHYsical Layer
PLCP	Physical Layer Convergence Protocol
PMD	Physical Medium Dependent
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RSU	Road-Side Unit
RTS/CTS	Request-To-Send/Clear-To-Send
SME	Station Management Entity
SPAWN	Swarming Protocol for vehicular Ad-hoc Wireless Network
TCP	Transport Control Protocol
UDP	User Datagram Protocol
UMB	Urban Multi-hop Broadcast
UMTS	Universal Mobile Telecommunications System
V2I	Vehicle-to-Infrastructure
V2R	Vehicle-to-Roadside
V2V	Vehicle-to-Vehicle
V2V2I	Vehicle-to-Vehicle-to-Infrastructure
VANET	Vehicular Ad hoc Network
WAVE	Wireless Access in the Vehicular Environment
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Networks
ZOR	Zone of Relevance

Chapter 1 Introduction

1.1 Background to Study

Given the fact that today vehicles play an important role in peoples' lives, embedding software-based intelligence into cars has the potential to intensely improve the passengers' quality of life. Vehicular networks provide a promising platform for a much broader range of large scale, highly mobile applications. This, along with the high market demand for more reliability, safety and entertainment in automobiles, has resulted in massive development and support of vehicular networks and its applications [1]. Some of these applications are conventional mobile internet access applications, like downloading files, reading e-mail while on the move, etc. Others involve the discovery of local services in the neighbourhood by using the vehicle grid as an ad-hoc network, e.g., restaurants, movie theatres, etc. Others demand close interaction among vehicles such as interactive vehicle-based games. The demands of these applications give the list of requirements and challenges for vehicular applications.

Car manufacturers together with national government agencies have joined forces to come up with ideas and technologies that could assist drivers and commuters on the roads. This involves supplying of safety and comfort information. At the same time, universities and research organisations are working on adapting existing technologies and developing new ones for the vehicular networking environment. One such effort is the development and deployment of Intelligent Transportation Systems (ITS) which is the primary driver for the research on inter-vehicular communications [2]. ITS aims to minimize accidents and improve traffic conditions by introducing information exchange between vehicles, drivers and passengers through the use of wireless communication. The deployment of such information exchange mechanism is achieved by the implementation of wireless vehicular networking also known as Vehicular Ad hoc Network (VANET), Figure 1.1. As shown in the figure, interaction between two vehicles is enabled by the use of short range wireless technologies, Wi-Fi and or WAVE, depending on the interaction type. Furthermore, vehicles can connect to other infrastructure networks and the Internet through Wi-Fi hotspots or long/wide range wireless technologies, WiMAX and or cellular. Additionally vehicles can interact with the traffic operators and other concerned agencies through roadside units. Roadway information and route planning is often available from positioning systems and map-based technologies such as GPS.

Vehicular networking is an emerging technology that will enable vehicles to communicate with each other, vehicle-to-vehicle (V2V) communication, and with fixed roadside units or the Internet cloud, vehicle-to-infrastructure (V2I) communication, or a hybrid of the two, called vehicle-to-vehicle-to-infrastructure (V2V2I) communication[1,3,4]. VANETs are a special case of Mobile Ad hoc Networks (MANETs) where the nodes (vehicles) are characterised by high mobility on predictable paths or directions due to roadways, but unlike MANETs, they are not constrained in terms of energy and storage. The sudden speed and direction changes which cause rapid network topology changes impose a number of challenges [1, 5], for example, message routing due to short lived communication links, signal degradation due to Doppler effects and multipath fading, and medium access control of the shared wireless medium [6].

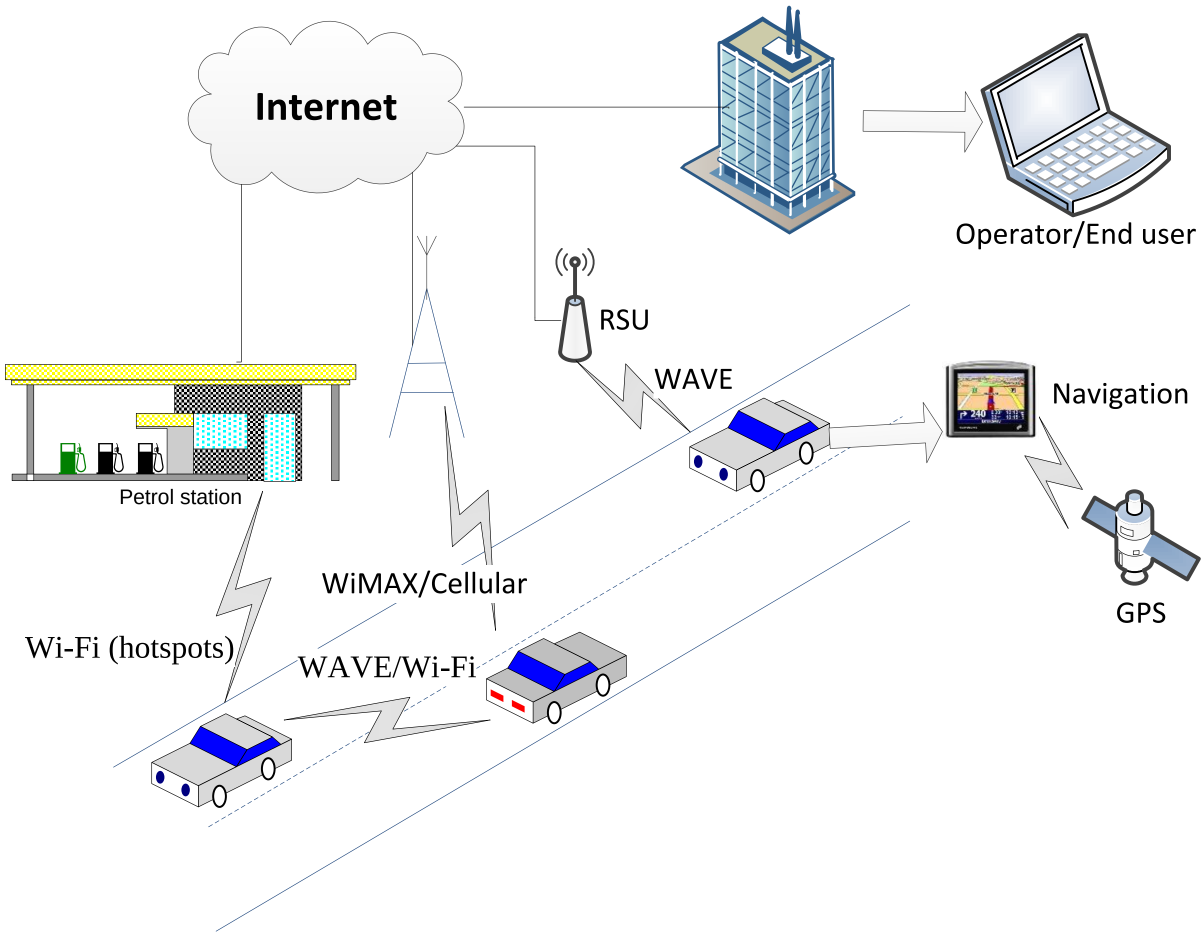


Figure 1.1. Illustration of a vehicular network

The ability to equip vehicles with sensing and control devices makes vehicles an ideal platform for mobile data gathering especially in the context of monitoring surrounding environments (i.e., vehicular sensor networks) [7, 8, 9, 10, 11]. Awareness of the immediate surroundings on the current location and interworking amongst vehicles can guarantee safe and efficient travelling. Compared to the traditional sensor networks, vehicular sensors have fewer constraints on processing power and storage capabilities, and they can generate and handle data at a higher rate. Therefore, each vehicle can then sense events, process sensed data and route the data to other vehicles. Moreover, the sensing coupled with the in-car navigation systems, high bandwidth wireless communications and protocols for mobile ad hoc networks can lead to a number of vehicular networking applications [12]. These applications could be then used to supply vehicles with traffic information that could make drivers aware of their surrounding environment, which in turn will assist them in making informed decisions and reacting timeously. In addition, the in advance warnings can prepare a vehicle's safety systems, such as anti-brake lock systems, air bags and pre-tension safety belts, in the event of an impending collision.

The applications proposed for VANETs can broadly be classified into safety and non-safety applications [13, 14]. Safety applications convey safety critical information based on sensor data from other cars or roadside units to report and avoid crashes and emergencies [1, 13]. Examples include a sudden brake warning sent from a remote preceding car, information about road conditions and maintenance, and accident annunciations. Non-safety applications, which have received less attention in the literature, include entertainment and information on general traffic management [1, 15, 16]. The non-safety applications (except some traffic management applications) typically obtain data on-demand such that a node requests information of interest [1, 14]. Examples of this are electronic payments, file sharing and audio video streaming. A key aspect of these commercial applications is the availability of high data rates and stable Internet connectivity.

VANET applications, which include safety messaging, traffic management and Internet access, have different requirements of data rates, latency and infrastructure [17, 18]. Traffic applications have relatively relaxed latency constraints and involve collecting information from several sources (vehicles, road based sensors, highway cameras). Such applications can be instantiated without infrastructure support, enabled by multi-hop communication and networking. Safety communications, however, is concerned with exchanging state with nearest neighbours to maintain safety in the system. As a result, the profile for data exchange is expected to be of high frequency of updates with a small payload. A strict requirement is high reliability of messages delivered, that is, the packet delivery ratio (PDR) and the average delay of messages delivered.

When sharing a single communication medium, an important factor is the prioritization of messages; safety applications should have higher priority. But sometimes non-safety applications could already have flooded the network causing delay of critical messages. As mentioned in [22], for VANETs to support different safety and non-safety applications with different quality of service (QoS), nodes need to follow protocols that will enable them to cooperate with each other. Thus a quality level of minimum latency and maximum reliability cannot be achieved if existing radio bands are used and/or safety and non-safety communications share the same frequency and bandwidth [35]. This necessitates the need for a multi-channel radio system, having separate channels for both safety and non-safety applications.

The Wireless Access in the Vehicular Environment (WAVE) specifications employs the multi-channel technique by leveraging on the channel switching scheme. This recently introduced standard, WAVE, (IEEE 802.11p) [21] is an enhancement of IEEE 802.11 to support ITS applications, operating on the licensed spectrum from 5.85 to 5.925GHz, occupying 75MHz. Alternatively, a realisation of WAVE could be used for safety applications while the existing standards, like IEEE 802.11 (Wi-Fi) and IEEE 802.16 (Mobile WiMAX), could be used for non-safety applications. Thus, employ the context of the coexistence of different communication technologies for serving connectivity requirements in the vehicular environments. Separating the applications by applying cross layer architecture, as shown in Figure 1.2 below [22] can also improve overall system performance and efficiently utilize resources.

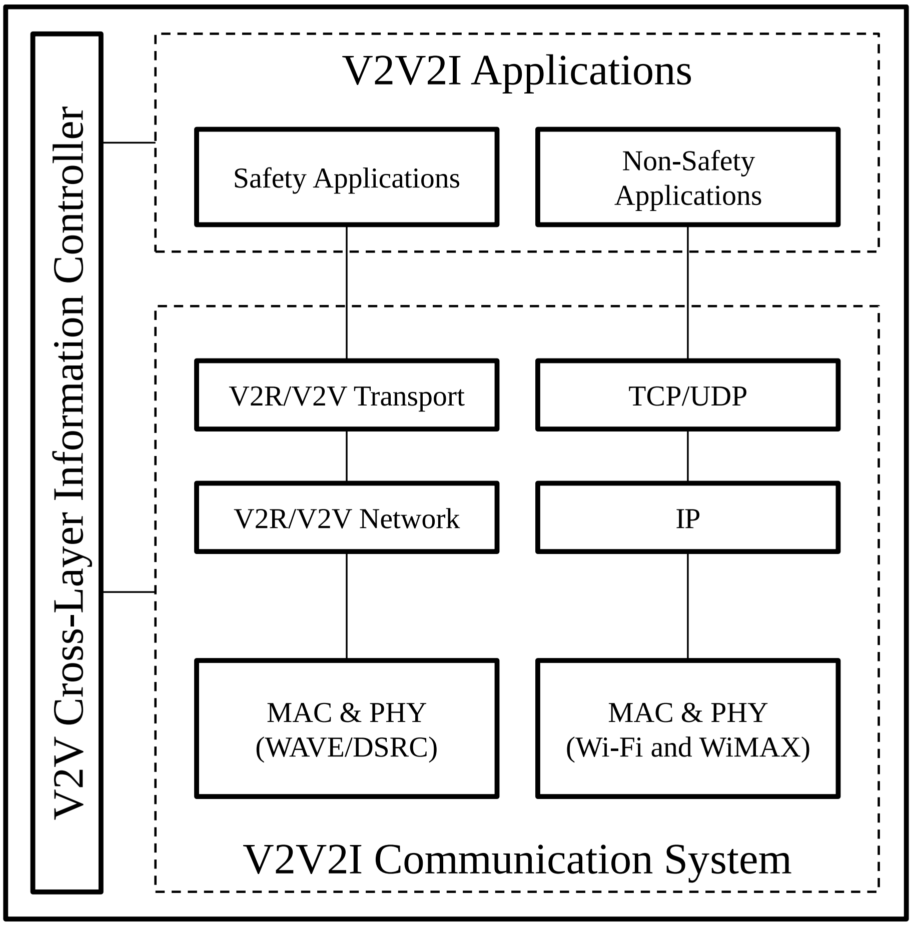


Figure 1.2. V2V2I system components and functionality

Wi-Fi is a short range (+/-200 m) wireless local area network (WLAN) technology protocol based on the IEEE 802.11 network standard [23] operating on an unlicensed radio frequency of 2.4 GHz offering high data rates of up to 150 Mbps (IEEE 802.11n [24]). In this investigation, IEEE 802.11n was used because it builds on previous 802.11 standards by using only orthogonal frequency division multiplexing (OFDM), adding multiple-input multiple-output (MIMO) and doubling of channel width 40 MHz channels to the PHY (physical layer). WiMAX is a long range wireless metropolitan area network (WMAN) technology providing up to 30 miles (50 km) for fixed stations, and 3 - 10 miles (5 - 15 km) for mobile stations. It is based on the IEEE 802.16 standard [25] currently covering spectrum ranges from 2 GHz range through 66 GHz range, with non-line-of-sight offered on lower frequencies, 2 – 11 GHz, and line-of-sight offered on frequencies up to 66GHz. WiMAX is further categorised in fixed WiMAX (IEEE 802.16d-2004) and mobile WiMAX (IEEE 802.16e-2005). We chose WiMAX because it is one of the next generation technologies

(NGN) currently available, but due to the limitation of equipment IEEE 802.16d-2004 was used instead of a more suitable IEEE 802.16e.

1.2 Problem Specification

Vehicular networks have no fixed infrastructure and instead rely on the vehicles themselves to provide network functionality. However, due to mobility constraints, driver behaviour and high speeds, connectivity in VANETs is not always guaranteed. Like in other networks, VANET applications have different requirements in terms of QoS i.e. latency/delay, data rates, size of content to be distributed, distribution area, and push/pull based, number of recipients (unicast/multicast/broadcast) and some are even interactive applications.

The lack of connectivity in vehicular networks can be an advantage for safety applications since when the network is not connected (meaning vehicles are far apart) there is basically low risk in terms of safety. On the other hand, commercial applications require constant connectivity among vehicles to enable content and data sharing; hence the focus in this research. In networking terms, data delivery is enabled by protocols; in particular for VANETs, the protocols can be categorised as Geographical routing, Trajectory based routing, and Opportunistic routing. But because communication links are usually short lived in VANETs, content downloading and or uploading can only be done in blocks. Thus, when designing these protocols, content data retrieval and indexing needs a special attention.

This research aims to give a thorough understanding of how vehicular networks will perform under realistic vehicular environments which will in turn help in the development of VANET applications and protocols. Because the focus is on commercial applications, quantitative aspects of connection performance under various motional and environmental conditions include:

- Contact time (duration) of a typical communication link; some applications require long lived connections while others can survive on short lived connections. Therefore this aspect will help to choose which link a node can use to communicate on, for a particular application.
- Amount of data that can be transferred during a contact period; this is tested on different behaviours in vehicular environment, from vehicles travelling in opposite directions to vehicles following each other. Knowing the amount of

data that can be uploaded/downloaded for particular link duration will help in creating data blocks and indexing.

- Instantaneous throughput while the link is active; some applications require high throughput (e.g. voice/video) hence a decision to start an application can be based on this aspect.
- Amount of jitter evident on the link; commercial applications are not strict in terms of delay but others are sensitive to jitter.

Due to short lived contact periods between vehicles, high data rate technologies prove to be more preferred in this type of networks. But because currently the long range wireless technologies support lower data rates compared to short range wireless technologies; both are used to provide higher data rates and wider coverage. This research therefore empirically examines the performance of a simple VANET that uses Wi-Fi and WiMAX to realise V2V2I network architecture as indicated in Figure 1.3. For the experiment Wi-Fi is used for V2V communication and WiMAX for V2I communication. With the focus on non-safety applications including Internet connectivity and media streaming, the network performance is evaluated in built and unpopulated urban environment. Wi-Fi performance for V2V communication is also investigated in a highway environment. The results show that the network architecture employed provides a robust and functional channel for V2V, V2I and V2V2I data delivery under specific scenarios.

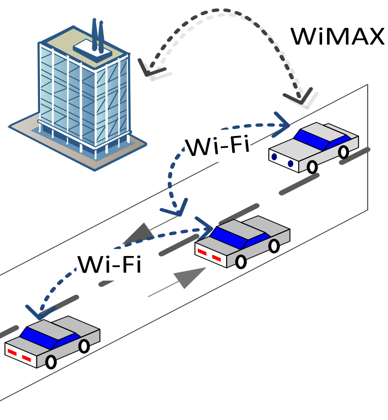


Figure 1.3. V2V2I architecture using Wi-Fi and WiMAX

1.3 Results Overview

The results have been logged and analysed, and they are encouraging as far as mobility and environmental conditions are concerned. The fixed experimental variables, nodes' speed and environment (LOS/NLOS), affect the network quantitative aspects differently. As expected, the contact time depends on communication range, node's direction and speed. On the other hand communication range is affected by the environment; the obstacles limit the maximum range that can be reached. The separation between the communicating nodes affects the signal strength which in turn affects throughput (thus data transferable) and jitter. Moreover, total data transferable as per connection depends on the contact period and throughput. The implementation of video and voice also added a value on the results as they showed the capability of an implemented network in terms of data handling.

These analytical results can help in development of routing protocols to predetermine the duration/lifetime of a particular found path. With this information, a link can either be used or dropped depending on an application of interest. Additionally, such a capability can lead to better implementation and classification of applications.

1.4 Thesis Outline

The remainder of this paper is organised as follows:

Chapter 2 gives the literature review and overview of related work. The unique challenges and characteristics of VANETs are discussed followed by presentation of communication architectures currently available in VANETs and a brief analysis of routing protocols that support vehicle-based applications is given, and finally an overview of available wireless technologies in relation to vehicular networks.

Chapter 3 describes the experimental setup and equipment used to conduct this research. This section presents factors and quantitative aspects that were taken into account when conducting the research. It further gives the technologies used and their configuration.

Chapter 4 presents the results and their analysis with respect to the conditions described in the previous section. The results are also compared to the findings in the literature.

Chapter 5 concludes the paper and gives the findings of the research.

Chapter 6 explores the envisioned future work to incorporate the findings of this research.

Chapter 2 Literature Survey

2.1 VANETs Characteristics and Challenges

VANETs have characteristics of topology and mobility similar to, yet distinct from traditional mobile ad hoc networks (MANETs). However, due to mobility constraints, drivers' behaviour, and high speeds, VANETs show characteristics that are completely different from conventional MANETs. In VANETs the nodes (vehicles) travel at high speeds mostly on predictable paths due to roadway topology: furthermore, they are less restricted in terms of available energy, computation and storage [26]. The VANET nodes have much higher power reserves than typical MANET nodes as they get their energy or power from batteries that are constantly being charged as needed from the engine. The VANET nodes have less size constraints than traditional MANET nodes, and therefore can support larger computing and sensing devices. Moreover, many of the sensing devices are needed for normal vehicle operation and already part of the vehicle. The abundant power source and larger size allows VANET nodes to be equipped with larger powerful computers and data storage as well as wireless devices with powerful transceivers supporting high data rates.

The use of wireless communication in VANETs presents specific challenges: As shown in [27], there are two issues at the link layer that affect the throughput, the problems of hidden nodes and exposed nodes. The hidden node problem occurs when two nodes outside the interference range of one another have one or more nodes that are within the transmission range of both. If they both try to transmit data at the same time, they cause a collision at one of the nodes they share. As shown in Figure 2.1, nodes A and C are outside the transmission range of each other but if they transmit to node B at the same time, a collision occurs.

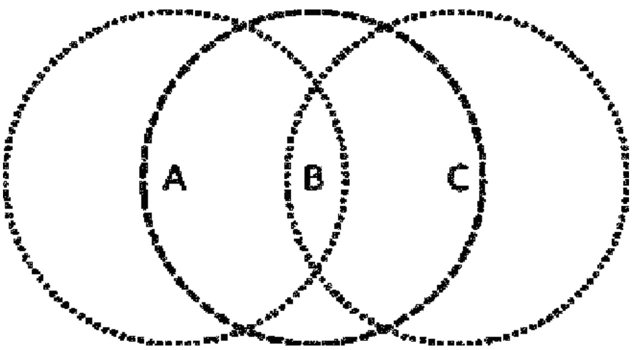


Figure 2.1. Hidden node problem: node A hidden from node C and vice versa

The exposed node problem occurs when two nodes are within interference range of each other but each has nodes outside interference range of the other. As shown in Figure 2.2, nodes A and C are within interference range of each other, but A has a neighbour B outside range of C, and C has a neighbour D outside range of A; hence nodes A and C could transmit to nodes B and D respectively without causing a collision at either B or D. However, because nodes A and C are within interference range of each other, only A or C could transmit at a time.

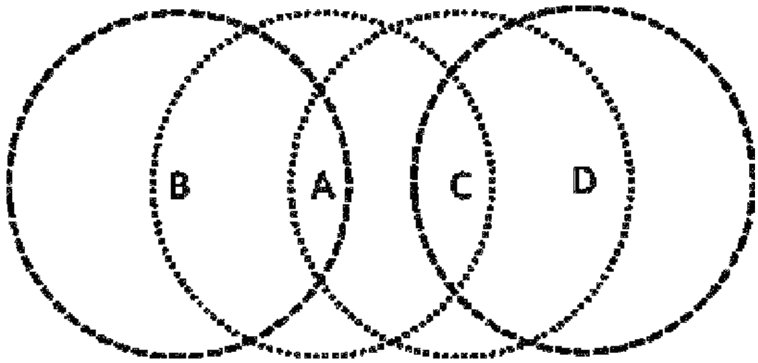


Figure 2.2. Exposed node problem: node A exposed to node C and vice versa

The effect of the hidden nodes problem on throughput is solved by employing request-to-send/clear-to-send (RTS/CTS) handshaking. However, the same mechanism cannot be employed on exposed nodes as both nodes will get CTS only to cause collision, making exposed nodes difficult to address. Thus exposed nodes present one of the factors that limit the network throughput. But As indicated in [28], a way of increasing the network throughput while holding traffic load constant is by increasing the number of nodes in the network. On the other hand, the nodes in VANETs are self-organising hence cannot be placed as needed.

Regarding vehicular network size, the authors in [29] observed that vehicles tend to travel in groups that are separated from each other. These blocks are called platoons. This behaviour can be exploited to improve the throughput in VANETs. The platoon characteristics depend on traffic density on roadways, which in turn varies in time (day or night) and space (urban or rural). During the day, with peak hours presenting denser traffic, there are more vehicles on the roads than at night. Urban areas tend to be densely populated while rural areas have sparse traffic. Hence the connectivity in the vehicular network varies between two extremes, that of fully connected network and of a sparse network with several partitions. Therefore, a VANET is characterized by time varying topology and connectivity [30]. With respect to connectivity, density plays a key role in enabling multi-hop communication: different vehicle densities cause disconnections where vehicles are not able to communicate. Thus, in networking terms, the nodes are partitioned from each other. As a result, message propagation in the network is constrained by the occurrence of partitions between nodes.

Network partitions and short lived paths between nodes caused by mobility present a challenge in the routing layer. This necessitates implementation of routing techniques that can efficiently handle fragmented networks and rapid topology changes. The currently available routing techniques, proactive and reactive, used in traditional MANETs fail to successfully handle these requirements for VANETs. Reactive protocols set up routes when a node tries to transmit data, but the VANET links are short-lived hence could disappear as soon as they are discovered. Proactive protocols on the other hand seeks to maintain routes to every node, but with rapid topology changes in VANETs will result in overhead of routing traffic as new routes will need to be discovered constantly. To overcome this challenge, the authors in [31] argue that location-based routing is more appropriate as messages are delivered to the nodes in the zone of relevance based on location stamp in the message. Routing in VANETs is discussed in more detail in Section 2.3.

The issues of security and privacy also need to be addressed in vehicular networks. Like in MANETs, because of lack of fixed infrastructure, nodes in VANETs rely on other nodes which are unreliable to propagate data. Fake messaging should be detected and enforcement of anonymity preservation for undependable parties to prevent vehicle tracking and identification. In MANETs, secure routing techniques have included cryptography, including hash chains and digital signatures, and the distribution of public key certificates to ensure the validity of routing messages [32, 33]. Other secure routing techniques require the use of redundant paths by using multiple routes to propagate messages. All these techniques increase message size, and require multiple paths hence limiting the throughput making them not suitable for limited short-lived links in vehicular networks.

In general, vehicles travel at high speeds, making sustained, consistent vehicular communication difficult to maintain. Thus high mobility and connectivity management in VANETs represent major challenges due to variable and random nature of such networks. These characteristics have important implications for design decisions in vehicular networks.

2.2 VANETs Communication Architectures

There are several possible network architectures to organise and connect the in-vehicle systems. Three alternatives include a pure wireless vehicle-to-vehicle (V2V) ad-hoc network, a wired backbone with wireless last-hops, with vehicle-to-infrastructure or vehicle-to-roadside (V2I or V2R), or a hybrid architecture using V2V communications that does not rely on a fixed infrastructure, but can exploit it for improved performance and functionality when it is available (V2V2I). The architecture discussed here is based on the architecture described by Car-to-Car Communication Consortium (C2C-CC) [35]. The C2C-CC has specified some architectural considerations for VANETs deployment; these include road-side units (RSUs) existing along the road and vehicle equipment called an on board unit (OBU) and some application units (AUs) executing a single or a set of applications. An infrastructure-based model utilises existing or new infrastructure such as cell towers or access points (Wi-Fi) to enable messaging. Therefore V2I can represent a viable solution for some applications to bridge the inherent network fragmentation that exists in any multi-hop network formed over moving vehicles.

OBUs and RSUs can be classified as nodes of a vehicular ad-hoc network, respectively presenting the mobile and static nodes. An OBU consists of wireless communication device(s). OBUs and RSUs can form ad-hoc networks which allow communications among nodes in a fully distributed manner without the need for a centralised coordinator. Communications between nodes can occur via single-hop or multi-hop fashion in cases of no direct connectivity between two communicating nodes. Multi-hop however requires dedicated routing protocols to assist data forwarding from one OBU to another, until data reaches the destination node. An RSU can be linked to an infrastructure network, which in return can be connected to the Internet. As a result, RSUs may allow OBUs to access the infrastructure. In this way it is possible for AUs registered with an OBU to communicate with any host on the Internet, when at least one infrastructure-connected RSU is available. An OBU may also be equipped with alternative wireless technologies for both, safety and non-safety. OBU may also communicate with Internet nodes or servers via public, commercial, or private hotspots (also referred to "Wi-Fi hotspots") operated individually at home or at office or by wireless Internet service providers. These two types of infrastructure domain access, RSU and HS, also correspond to different applications types. In cases where neither RSUs nor hotspots provide Internet access, OBUs can also utilize communication capabilities of cellular radio networks (GSM, GPRS, UMTS/LTE, HSPA, WiMAX, 4G) if they are integrated in the OBU, in particular for non-safety applications.

The On-Board Unit (OBU) is responsible for V2V and V2I or V2R communications. It also provides communication services to AUs and forwards data on behalf of other OBUs in the ad hoc domain. An OBU is equipped with at least a single network device for short range wireless communications based on IEEE 802.11p radio technology. This network device is used to send, receive and forward safety-related data in the ad-hoc domain. An OBU can be equipped with more network devices, e.g. for non-safety communications, based on other radio technologies like IEEE 802.11a/b/g/n. An Application Unit (AU) is an in-vehicle entity and runs applications that can utilize the OBU's communication capabilities. Examples of AUs are:

- a dedicated device for safety applications like hazard-warning,
- a navigation system with communication capabilities,
- a mobile device such as a PDA that runs Internet applications.

An AU can also be built into a vehicle (embedded) and be permanently connected to an OBU. This ensures that a minimal set of applications are always executed in the vehicle. Another type of AUs can dynamically be plugged into the in-vehicle network, for example a passenger's PDA. Multiple AUs can be plugged in with a single OBU simultaneously and share the OBUs processing and wireless resources.

A Road-Side Unit (RSU) is a physical device located at fixed positions along roads and highways, or at dedicated locations such as gas station, parking places, and restaurants. An RSU is equipped with at least a network device for short range wireless communications based on IEEE 802.11p radio technology. An RSU is likely equipped with other wireless network devices in order to allow communications with an infrastructure network. The main functions of a RSU are:

- To extend the communication range of an ad hoc network by means of re-distribution of information to an OBU when the OBU enters the communication range of the RSU. This functionality includes the case that a RSU directly forwards data in a wireless multi-hop chain with vehicles.

- To provide other safety applications, such as for V2I warning (e.g. low bridge warning work-zone warning), intersection controller, or virtual traffic sign, and act as information source and receiver, respectively.
- To provide Internet connectivity to OBUs when linked with the infrastructure.
- To cooperate with other RSUs in forwarding or in distributing safety information.

2.3 Routing and Data Dissemination in VANETs

A routing protocol governs the way that two communicating entities exchange information. The protocol includes the procedure in establishing a route, decision in data forwarding, and action in maintaining the route or recovering from routing failure [36].

The high mobility of nodes and the rapidly changing topology in VANETs makes it hard to maintain or even establish an end-to-end connection as intermediate nodes are not always present between source and destination. For the past few years, this has prompted researchers to find and investigate scalable routing protocols that are robust enough for implementation in VANETs [37, 38, 39, 40, 42, 43]. To cater for the unique characteristics and applications of VANETs, traditional MANET routing protocols have been modified [44]. These protocols have been designed and classified to deal with nodes' mobility: by discovering new routes (*reactive routing*), updating routing tables (*proactive routing*), using geographical location information (*position-based routing*), identifying and detecting stable vehicle configurations (*cluster-based routing*), using vehicle's movements to support message transportation (*geocast routing*) and using broadcasting to support message forwarding (*broadcast routing*) [45].

Proactive and reactive routing protocols use links' information that exists in the network to perform packet forwarding, and they are classified under topology based routing protocols. Proactive routing protocols keep the information on paths to other nodes of a network at all times even when the paths are not in use. The paths are updated periodically irrespective of the network size, available bandwidth and network load. Thus proactive routing is only suitable for small networks with limited mobility due to the overhead of maintaining the data on the full network topology at each node. For situations like those in VANETs where the network changes frequently, this type of protocols presents a drawback as the paths needs to be continually maintained, thus degrading the available bandwidth. This makes proactive routing inefficient for use in vehicular networks. Examples of this type include Destination-

Sequenced Distance-Vector (DSDV) routing and Optimized Link State Routing protocol (OLSR). On the other hand, reactive routing protocols determine a path on demand, that is, a path between communicating nodes is kept only when it is in use. This makes reactive routing more suitable in vehicular networks as the nodes use a limited number of routes. However, in VANETs, trying to find a route every time a communication is needed can be costly as a path may cease to exist almost as quickly as it was discovered. Examples include Dynamic Source Routing (DSR), and Ad hoc On-demand Distance Vector (AODV) routing.

Position-based routing protocols as explained in [46, 47] require the availability of the participating nodes' physical position. Each node periodically transmits beacons containing its current position to the neighbours, but this beaconing can create collisions in a network if no proper collision detection mechanism is employed. Position-based routing hence does not require the maintenance or establishment of routes. Thus position-based routing provides a more robust and efficient forwarding mechanism for dynamic network topology of VANETs. Here, routing depends on the destination's position embedded in the packet and the position of the next hop node, that is, the forwarding node's neighbour. According to [48], position-based routing protocol is based on a greedy forwarding mechanism where packets are forwarded to nodes that are geographically closer to the destination than the previous node. This guarantees that the position of the next hop to always be closer to the destination node than that of the current node. Naumov et al. [49] presented a protocol called Connectivity Aware Routing (CAR) for VANETs that can find connected paths between source and destination. Leontiadis et al. [50] describe a geographical opportunistic routing protocol suitable for vehicular networks which employs the VANETs topology and the geographical routing information. Other examples of position-based routing include Greedy Perimeter Stateless Routing (GPSR) [48] and Distance Routing Effect Algorithm for Mobility (DREAM) [51].

Cluster-based routing requires a formation of a virtual network infrastructure through the clustering of nodes. Each cluster has a cluster-head which coordinates and manages the network; it is responsible for communications within and outside the cluster. Even though cluster-based routing protocols can perform well for large networks, delay and overhead involved in forming and maintaining the clusters imposes a significant barrier for them in fast-changing VANET. Blum et al. [52] proposed a Clustering for Open IVC Networks (COIN) algorithm; cluster-head selection is based on vehicular dynamics and driver intentions. The algorithm also accommodates the unstable nature of vehicle-to-vehicle distances.

Geocast routing is basically a location-based multicast routing [53, 54] where a multicast group is defined to be a certain geographical region. In geocast routing the packet is delivered from a source node to other nodes within a specified geographical region termed Zone of Relevance (ZOR). Most geocast routing methods are based on directed flooding, which tries to limit the message overhead and network congestion of simple flooding by defining a forwarding zone and restricting the flooding inside it. Maihofer et al. [55] proposed abiding geocast, a time stable geocast where messages are delivered to all nodes that are inside a destination region within a certain period of time and discussed design space, semantics, and strategies for abiding geocast. Chen et al. [56] presented a spatiotemporary geocast routing protocol, called mobicast protocol designed to support applications which require spatiotemporary coordination in VANETs. The protocol forwards a mobicast message to vehicles located in some geographic zone at time t, where the geographic zone is denoted as ZOR.

Broadcasting strategies have been proposed in literature to address message dissemination for safety related applications to all nodes located close to the sender with high delivery rate and short delay [57, 58]. Korkmaz et al. [59] introduced Urban Multi-hop Broadcast (UMB) aiming to improve reliability of broadcasting. In UBM, a hidden terminal problem is solved through an RTS/CTS-style handshake. UBM further alleviates the broadcast storms through black-burst signals to select a forwarding node that is farthest from the sender using location information. Unlike UMB, Broadcast Medium Window (BMW) [60] and Batch Mode Multicast MAC (BMMM) [61] require all the receiving nodes to send back an ACK to the sender in order to achieve reliability. Biswas et al. [63] studied two different types of forwarding techniques, naive and intelligent broadcasting. In naive broadcasting, a broadcast message is sent periodically among vehicles at regular intervals. A drawback of this technique results from the number of forwarded messages; as message collisions increase, the delivery time also increase thus lowering the message delivery rate. Intelligent broadcast protocol solves this problem by limiting the number of messages broadcast within the platoon for a particular event. If the event-detecting vehicle receives the same message from behind, it assumes that at least one vehicle in the back has received it and stops broadcasting, thus improving the overall system performance.

2.4 VANETs Applications and Classification

Roadway safety has always been the driving force in establishing inter-vehicle communications, but VANETs also present a promising platform for a much broader range of large scale, highly mobile applications. VANETs are expected to provide a wide range of applications in transportation systems; ranging from accident avoidance messaging, real-time traffic updates and monitoring, remote diagnostics and general information services like Internet access and in-car infotainment [67]. Therefore, vehicular networking applications can typically be characterized in three distinct classes; *safety applications*, *traffic and map-related applications* and *infotainment applications* like Internet access or general purpose data exchange [65, 66]. Data exchange and messaging requirements for each class of applications has different requirements for communication parameters in terms of latency, data rate requirements and quality of service in general [67, 17]. Safety applications are normally composed of low latencies and small payload messages distributed over short ranges. On the other hand, traffic information systems are designed to gather and manipulate data originating from other vehicles and roadside units in relatively large areas. The data delivery in this class is delay tolerant and the messages can be large, but with relaxed latency requirements. Similarly, infotainment applications, Internet and in-vehicle entertainment systems, have large payload messages with a requirement of high data rates.

Safety applications are typically based on broadcast communication, where data is flooded in a geographic target area. These applications have strong demands with respect to reliability and delay. The time-sensitivity in these applications requires data to be retrieved or disseminated to the desired nodes within a given time window, failure to do so renders the data useless. Moreover the applications' data gathered from vehicles and data consumed by vehicles are highly location-dependent, meaning delivery of data outside its intended area is also regarded useless.

In contrast, non-safety applications, also known as comfort applications, rely on point-to-point (unicast) communications and have less stringent requirements for reliability and delay. These applications' content distribution to vehicles ranges from multi-media files to road condition data and to updates/patches of software installed in the vehicle. Most of these applications are delay-tolerant hence require persistent and reliable storage of data for later retrieval. In addition, they require networking protocols (including sophisticated query processing) to efficiently locate/retrieve data of interest. For example, VANETs provide Internet connectivity to vehicular nodes while on the move so the users can download music or play games. Usually, some fixed or dynamic assigned network-to-Internet gateways are added to the networks, so they can deliver the messages between the VANET and the Internet.

In general, the vehicles can be both significant producers and consumers of data. Their local resources are capable of supporting high fidelity data retrieval and playback. For the duration of each trip, drivers and passengers make up a captive audience for large quantities of data. Examples include [74, 70, 37, 72, 71, 76, 73, 75, 69]:

- locality-aware information - these applications require location aware data gathering/retrieval and or dissemination e.g. map based directions, road conditions and accidents, traffic congestion monitoring, ads and emergency neighbour alerts
- content for entertainment - these applications require high throughput network connectivity and fast access to desired data e.g. streaming movies, music
- Also, interactive applications – these applications require high throughput as well as real-time communication among vehicles e.g. voice over V2V and online gaming.

All of the above applications require vehicles to play an intermediary role. Vehicles cooperate with each other to improve the quality of the users' experience for the entire network. Specifically, vehicles will provide temporary storage (caching) for others, as well as forwarding of both data and queries for data. In this capacity, they require reliable storage as well as efficient routing to the location of data sources and consumers.

2.5 Wireless Access Methods in VANETs/Access Technologies

Message dissemination in VANETs is primarily enabled with wireless radio technologies [77]. Vehicular networking can be achieved with short, medium, or long-range communication technologies. However, there are trade-offs in the adoption of these technologies including data capacity, continuity of connections and contention with other users. An access technology typically contains only the two lowest layers in the ISO OSI stack, namely the physical (PHY) and the data link (DLL) or media access control (MAC) layers.

Network connectivity to on-board computers can be also provided via pre-existing cellular and Wi-Fi cells, due to new emerging technologies, Heterogeneous Wireless Network (HWN) scenarios, and multi-mode devices with several network interface cards (e.g., iPhones, smartphones, Personal Digital Assistant (PDA), etc.) [78]. For this purpose, Intelligent Vehicular Ad-Hoc Networking (InVANET) defines a smart novel way of using vehicular networking by integrating on multiple wireless technologies, such as 3G cellular systems, IEEE 802.11, and IEEE 802.16e, for effective V2I communications [78].

2.5.1 Short/Medium Range Wireless Technologies

The short or medium range wireless technologies that are used to form Wireless Local Area Networks (WLAN) exist in two different standards: HIPERLAN from European Telecommunications Standards Institute (ETSI) [79] and 802.11 from Institute of Electrical and Electronics Engineers (IEEE) [80]. Today the WLAN market, sometimes referred to as wireless Ethernet or Wireless Fidelity (Wi-Fi), is dominated by the IEEE 802.11 standard.

The IEEE 802.11 WLAN protocols are part of the 802 family that standardises Local Area Networks (LAN) and metropolitan area networks (MAN). The 802 family has a common Logical Link Control layer (LLC), which is standardised in 802.2. Below the LLC, the Media Access Control layer (MAC) and the corresponding physical layer (PHY) are packed together in the same standard subgroup. One of such standards subgroup exists as WLAN and is specified in 802.11. The IEEE 802.11 standard places the specifications for both the physical layer and for the medium access control layer.

The MAC layer, Figure 2.3 below, consists of a set of protocols responsible for maintaining order and management in the use of a shared medium. Two sub-layers are further defined in the MAC layer, the distributed coordination function (DCF) and point coordination function (PCF). The control and management in the MAC layer is done by the Station Management Entity (SME) and the MAC Layer Management Entity (MLME). DCF and PCF are used to control the medium access in order to provide ease of access and avoid collisions. DCF employs two different access methods, CSMA/CA and RTS/CTS. In CSMA/CA, when a node has data to transmit, it first listens to the medium to check if it is in use, where it will transmit if free or otherwise wait. On the other hand, in RTS/CTS, a node sends an RTS (Request To Send) and waits for CTS (Clear To Send) before it can begin transmitting. In case of collision when sending RTS/CTS, a node backs-off for a random period of time. An RTS includes the duration of time that a node wishes to occupy the medium. The nodes that share the same medium create a timer called a network allocation vector (NAV) that indicates how long they should wait before they are allowed to check the medium idleness. In general, each time a node accesses the medium and sends an RTS frame, other nodes start their NAV. Therefore each node checks its NAV to see if it has expired before sensing the idleness of the medium. In PCF, the access point polls nodes according to a list allowing them to transmit data one after another. There will be no collision since the list is controlled by the access point, therefore also not suitable for use in ad hoc mode.

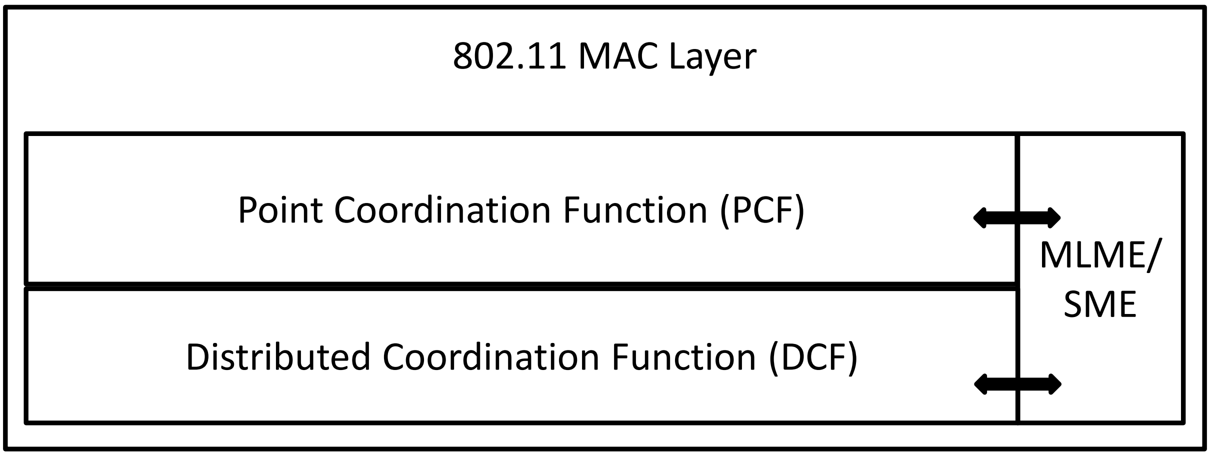


Figure 2.3. IEEE 802.11 MAC Layer

The physical layer, Figure 2.4 below, can further be divided into two parts: the Physical Layer Convergence Protocol (PLCP) and the Physical Medium Dependent (PMD). Responsible for the control of these sub-layers is the Physical Layer Management Entity (PLME). The PLCP provides a method for mapping the MAC sub-layer protocol data Units (MPDU) into a framing format suitable for sending and receiving data and management information using the associated PMD system. It is also responsible for carrier sensing, clear channel assessment and basic error correction. The PMD interacts directly with the physical medium and performs the most basic bit transmission functions of the network. It is mainly responsible for encoding and modulation.

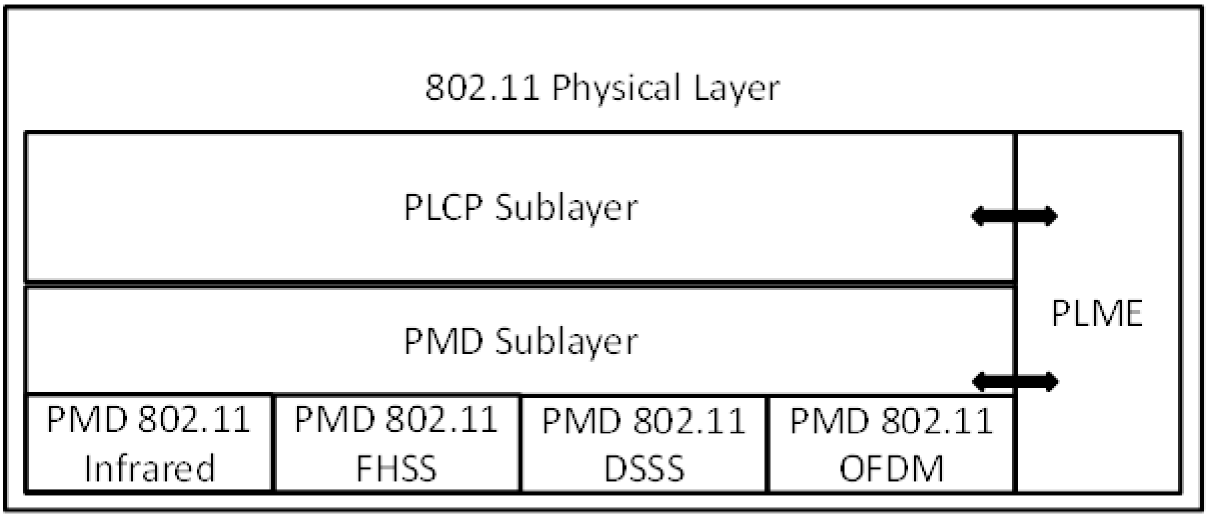


Figure 2.4. IEEE 802.11 PHY Layer

The IEEE 802.11 standard specifies two different types of a wireless network configuration; one is ad-hoc mode configuration and the other is called infrastructure mode configuration. The infrastructure mode uses access points over which wireless nodes can communicate. These network access points are usually connected to the wired LAN's to extend its capability. The access point acts as a bridge to allow wireless nodes to connect to other wired nodes. In an ad hoc mode configuration, there is no fixed structure to the network, nodes within each other's communication range can communicate and form a network without the access point.

IEEE 802.11a/b/g/n - Wi-Fi: The original IEEE 802.11 standard was completed in 1997. It provided three initial standards for the physical layer (PHY) [81]. Two of the three standards radio-based PHYs were specified to operate at 2.4 which is part of the unlicensed frequency range known as the ISM (Industrial, Scientific, and Medical) band [82, 83].The former was a frequency hopping spread spectrum (FHSS) PHY and the latter a direct-sequence spread spectrum (DSSS) PHY. Finally, an infra-red (IR) PHY, operating at baseband, was also described. The above PHY layers were all designed to support 1Mbps (Megabits per second) and 2Mbps rates. Data rate, range, throughput, and compatibility vary among WLAN standards. These variations are caused by differences in frequency, and modulation schemes.

In 1999, two amendments were added to the IEEE 802.11 standard, namely IEEE 802.11a and IEEE 802.11b. The IEEE 802.11b amendment introduced an extension to the previously-defined PHY with DSSS, to provide additional data rates of up to 11 Mbps in the

2.4GHz spectrum, using a modulation scheme known as complementary-code keying (CCK). The four data rates of 1, 2, 5.5, and 11 Mbps are specified on up to 3 non-overlapping channels and the lowest two rates are also allowed on up to 13 overlapping channels. IEEE 802.11a, specified a new radio-based PHY at 5.2 GHz to provide higher data rates using Orthogonal Frequency Division Multiplexing (OFDM) modulation on up to 12 discrete channels allowing for data rates of 6, 9, 12, 18, 24, 36, 48, 54 Mbps. The IEEE 802.11g standard was ratified in 2003 to extend the 2.4-GHz unlicensed spectrum to data rates faster than 20 Mbps. This standard defines a PHY layer with similar specifications to IEEE 802.11a, use of OFDM, and PHY rates up to 54 Mbps, but based on a 2.4 GHz carrier to support backward compatibility with IEEE 802.11b.

IEEE 802.11n: In late 2003, the IEEE formed the TGn task group to start work on the specification and development of the IEEE 802.11n amendment to allow data rates of at least 100 Mbps. This was to double the existing maximum data rate of 54 Mbps for the 802.11a/g specifications to support user applications with high data rate requirements e.g. high-quality video streaming for multiple users: and also to improve quality-of-service (QoS) as well as range. To achieve the increased throughput and range envisioned for IEEE 802.11, the 11n amendment specifies enhancements to both the physical (PHY) and medium access control (MAC) layers. Improvements to the MAC layer include the addition of frame aggregation, block acknowledgement (ACK) enhancements, a reverse direction (RD) protocol as well as schemes for co-existence with legacy devices. The PHY layer includes the use of multiple-input multiple-output (MIMO) antennas.

Frame aggregation in IEEE 802.11n has been achieved by sending multiple MAC frames in one PHY layer packet to reduce the protocol overhead due to frame headers and inter-frame gaps. The shorter the frames, the lower the efficiency of transport due to the overhead of headers and inter-frame gaps. The Aggregated MAC Service Data Unit (A-MSDU) mechanism increases the maximum size of the 802.11 MAC frames from the legacy 2304 bytes to 8k bytes. The Aggregated MAC Protocol Data Unit (A-MPDU) mechanism increases the maximum size of the 802.11 frames transported on the air link from the legacy 2304 bytes to 64k bytes.

The block ACK mechanism sends a single block ACK frame to acknowledge several received frames, this also reduces overhead hence can significantly improve protocol efficiency and throughput. While the block ACK protocol has been defined for legacy systems, it has not been extensively deployed. The 802.11n has reduced the size of the block ACK frame from the legacy 128 bytes to 8 bytes, which represents a significant improvement in air-link efficiency considering the frequency of the ACK frames on the air-link. In the legacy 802.11 a/b/g systems an acknowledgment (ACK frame) is sent from the receiving station to the transmitting station to confirm the reception of each frame. If the transmitter does not receive an ACK, it retransmits the frame until an ACK is received. The ACK mechanism is also used in rate adaptation algorithms so that if too many retransmissions are required, the transmitting station drops to a lower data rate. The ACK mechanism adds robustness to 802.11 and ensures that all transmitted frames eventually get to the receiver, but this robustness comes at the price of protocol efficiency since for each transmitted frame, an additional ACK frame is also sent.

The IEEE 802.11n PHY layer standard is based on MIMO air interface technology. MIMO uses spatial multiplexing to transport two or more data streams simultaneously in the same frequency channel. The use of spatial multiplexing can double the throughput of a wireless channel when two spatial streams are transmitted. In order to allow generation multiple spatial streams, one requires multiple transmitters, multiple receivers and distinct uncorrelated paths for each stream through the medium. Multiple paths can be achieved using antenna polarization or multipath in the channel. Multipath represents a scenario, where the signal reflects from walls and other obstacles. Reflections combine and form the signal distortions at the receiver. In the legacy 802.11a/b/g radios, the effects of multipath are devastating, but the multi-transmitter MIMO radios use multipath to an advantage. Each multipath signal is processed on the receivers in MIMO systems, helping in eliminating the mixture of out-of-phase signals which often result in signal distortion. A MIMO system has some number of transmitters (N) and receivers (M). Signals from each of the N transmitters can propagate to each of the M receivers through a different path. MIMO works best if these paths are spatially distinct, resulting in received signals that are uncorrelated. Multipath helps de-correlate the channels and thus enhances the operation of spatial multiplexing. Apart from spatial multiplexing, 802.11n devices can also use the traditional styles of receiver spatial diversity, such as Maximum Ratio Combining (MRC). The standard also introduces transmitter spatial diversity techniques, such as Space Time Block Coding (STBC) and Cyclic Shift Diversity (CSD), to improve reception by spreading the spatial streams across multiple antennas or transmitting the same signal with different cyclic shifts.

Other modifications include:

- Quality of Service (QoS) features, to support delay-sensitive applications such as Voice over WLAN and multimedia streaming (described in 802.11e),
- power save multi-poll (or PSMP) feature, a battery saving feature for WLAN in handheld devices,
- extended channel switch announcement, i.e., allowing an Access Point (AP) to switch between support of 20 MHz only, and 20 MHz/40 MHz (described in 802.11y),
- improved radio resource management, i.e., efficient use of multiple APs within a network (described in 802.11k),
- support for fast roaming, i.e., fast handoffs between base stations, intended for use in supporting mobile phones using VoIP and wireless networks instead of cellular networks (described in 802.11r).

IEEE 802.11p - DSRC/WAVE: DSRC protocol (Dedicated Short-Range Communication) is the name of the 5.9 GHz Band (5.850 − 5.925 GHz) allocated for the ITS communications designed to support high speed, low latency vehicular networks using the IEEE 802.11p [21] and WAVE (Wireless Access in Vehicular Environments) standards [84]. WAVE which is currently under development is also defined as the mode of operation used by IEEE 802.11 devices to operate in the DSRC band [85]. The main purpose of WAVE is to define standards and protocols to enable inter-vehicle communication (V2V) and communication between vehicles and infrastructure (V2I/V2R). To support travellers' safety and private applications for convenience in vehicular networks [86], the DSRC was allocated to use:

- 75MHz bandwidth at 5.9GHz band in the U.S.,
- 20MHz bandwidth at 5.8GHz band in Europe and
- 80MHz bandwidth at 5.8GHz band in Japan.

Figure 2.5, [87, 88, 89], shows the 75 MHz spectrum allocation for DSRC in the 5.9 GHz band by the U.S. FCC (Federal Communications Commission). The spectrum is divided into seven channels each 10MHz wide; one control channel (ch178) dedicated for safety communications only, two channels reserved for accident avoidance and high-powered public safety (ch172, ch184), and four service channels (ch174, ch176, ch180, ch182) for both safety and non-safety purposes. In Europe the standardisation process is mainly driven by

Car-2-Car Communication Consortium (C2C-CC) by preparing and supporting activities like the frequency allocation process, and the final standardisation is carried out in ETSI.

Frequency (GHz)	**5855**	**5865**	**5875**	**5885**	**5895**	**5905**	**5915**	**5925**
Channel	**Ch 172**	**Ch 174**	**Ch 176**	**Ch178**	**Ch 180**	**Ch 182**	**Ch 184**	
	Accident avoidance, safety of life	*Service Channel*	*Service Channel*	Control Channel	*Service Channel*	*Service Channel*	High power, long range	

Figure 2.5. DSRC spectrum allocation and channels in the U.S.

In a WAVE environment, RSU (sometimes other OBUs) announces the available services (safety or non-safety) on the corresponding channel. OBU listens to the services offered and executes safety applications first, and then switches channels to execute non-safety applications. This is achieved by OBU periodically switching between control channel, to listen to alert or warning messages, and one of the service channels, to receive/send other non-safety messages. As stated by the IEEE 1609.4, the channel time is divided into synchronization intervals with a length of 100 ms, consisting of 50 ms alternating control channel and service channel intervals.

The implementation is a broadcast method aims to enable vehicles to share state information in a fast and efficient manner with minimal setup time. In order to handle the fast topology changes of VANETs, the 802.11 Basic Service Set (BSS) is replaced in 802.11p with a WAVE BSS (WBSS). To form a WBSS, an RSU or OBU sends broadcast message, a WBSS announcement message called the WAVE Service Advertisement (WSA), on the control channel that contains the information that identifies the available services and associated network parameters necessary to join a WBSS, these include the WBSS identifier, the selected service channel, timing information for synchronization purposes. Unlike in traditional WLANs, forming a WBSS in 802.11p does not require active scanning, association, and authentication procedures. Therefore any node is allowed to transmit in a WBSS as long as the node has received a WBSS announcement from a WBSS provider [90, 91].

DSRC is expected to support vehicle speeds of up to 120 mph, with transmission range of up to 1000m and data rates of 6 Mbps and up to 27 Mbps. Table 1, [92], shows the DSRC regional standards in use for Europe, Japan and US. The DSRC radio technology is being standardised as IEEE 802.11p by modifying the 802.11 standard to add support for wireless local area networks (WLANs) in a vehicular environment. The 802.11p amendment is based on the IEEE 802.11a by introducing some modifications to the PHY (physical) layer and MAC (medium access control) layer in order to achieve a robust connection and a fast setup for moving vehicles.

Table 1. DSRC Regional Standards

	Japan (ARIB)	Europe (CEN)	U.S. (ASTM)
Duplex	OBU: Half-duplex RSU: Full-duplex	Half-duplex	Half-duplex
Frequency Band	5.8 GHz band 80 MHz bandwidth	5.8 GHz band 20 MHz bandwidth	5.9 GHz band 75 MHz bandwidth
Channels	Downlink: 7 Uplink: 7	4	7
Channel Separation	5 MHz	5 MHz	10 MHz
Data Rate	Down/Uplink 1 or 4 Mbps	Downlink/500 kbps Uplink/ 250 kbps	Down/Up-link 3-27 Mbps
Range	30m	15 - 20m	1Km (max)
Modulation	2-ASK (1Mbps) 4-PSK (4Mbps)	RSU: 2-ASK OBU: 2-PSK	OFDM

Where:

ARIB: Association of Radio Industries and Businesses

CEN: European Committee for Standardization

ASTM: American Society for Testing and Materials

OBU: On-Board Unit

RSU: Road Side Unit

ASK: Amplitude Shift Keying

PSK: Phase Shift Keying

OFDM: Orthogonal Frequency Division Multiplexing

The IEEE 802.11p MAC layer is designed to be PHY layer independent, and is enhanced by the 1609.4 in the IEEE 1609 family of protocols [93] to allow for multi-channel operation [94]. The MAC layer uses the prioritised and contention-based Enhanced Distributed Channel Access (EDCA) scheme of 802.11e [95], which is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme [6]. In a basic EDCA access scheme, if packets from different queues in the same station compete for the access, a virtual resolution function will resolve the conflict by assigning the transmission opportunity to the packet with the highest priority, while the lowest priority packet will be retransmitted or discarded if a maximal number of retries has been reached. To cater for the multi-channel WAVE environment, 802.11p's access mechanism is modified by implementing two separate EDCA functions, one for control channel and one for service channels, each handling different sets of queues for packets destined to be transmitted on different channel.

The 802.11p PHY layer is based on the orthogonal frequency division multiplexing (OFDM) which is the same PHY layer used in the IEEE 802.11a standard, but with some changes. OFDM is a special case of Frequency Division Multiplex (FDM) where the signal is first split into independent channels, modulated by data and then re-multiplexed to create the OFDM carrier. The changes in the IEEE 802.11p Physical Layer are shown in Table 2 where the PHY Layer values of the 802.11a and 802.11p implementations are compared. Three different PHY Layer modes are defined in the previous IEEE 802.11 standards, the 20 MHz, 10 MHz and 5 MHz modes. These different modes are achieved by using different sampling (clock) rates. IEEE 802.11a usually uses the full clocked mode with 20 MHz bandwidth while IEEE 802.11p targets the half clocked mode with 10 MHz bandwidth. The half clocked mode in IEEE 802.11p affects the following parameters:

- Bandwidth - the 10 MHz bandwidth is used in IEEE 802.11p so as to make the signal more robust against fading with an option of the 20 MHz bandwidth implementation. If the optional 20 MHz channels, ch175 (combination of ch174 and 176) and ch181 (combination of ch180 and ch182) are used, data rates up to 54 Mbps can be obtained.
- Carrier spacing - the carrier spacing is reduced by ½ in IEEE 802.11p signal compared to that of IEEE 802.11a.

- Symbol length - the symbol length is doubled, making the signal more robust against fading in IEEE 802.11p.
- Frequency - the 802.11p standard operates in the 5.8 GHz and 5.9 GHz frequency bands depending on regional regulatory authorities' regulations.

Table 2. Comparison of physical layer implementations in IEEE 802.11a and IEEE 802.11p

Parameters	IEEE 802.11a	IEEE 802.11p	Changes (to 802.11p)
Bit rate (Mbit/s)	6, 9, 12, 18, 24, 36, 48, 54	3, 4.5, 6, 9, 12, 18, 24, 27	Halved
Modulation	BPSK, QPSK, 16QAM, 64QAM	BPSK, QPSK, 16QAM, 64QAM	Similar
Code rate	1/2, 2/3, 3/4	1/2, 2/3, 3/4	Similar
Number of subcarriers	52	52	Similar
Symbol duration	4 µs	8 µs	Doubled
Guard time	0.8 µs	1.6 µs	Doubled
FFT period	3.2 µs	6.4 µs	Doubled
Preamble duration	16 µs	32 µs	Doubled
Subcarrier spacing	0.3125 MHz	0.15625 MHz	Halved

2.5.2 Wide/Long Range wireless technologies

WiMAX: Worldwide Interoperability for Microwave Access (WiMAX) was introduced by an industry consortium called the WiMAX Forum [96]. WiMAX is targeted to conceive a system for combined fixed and mobile broadband wireless access. Currently the WiMAX Forum has two different system profiles IEEE 802.16d-2004 called fixed system profile and IEEE 802.16e-2005 called the mobile system profile. The differences in these two profiles are shown in Table 3.The technology is based on the IEEE 802.16 group of standards. IEEE 802.16 was formed in 1998 to develop the air interface, MAC and PHY, for wireless broadband systems. The higher-level networking specifications for WiMAX systems are developed by WiMAX Forum Network Working Group (NWG).

Table 3. IEEE 802.16 Standards comparison

	802.16d-2004	802.16e-2005
Frequency band	2 – 11 GHz	2 – 11 GHz fixed, 2 – 6 GHz mobile
Application	Fixed NLOS	Fixed and mobile NLOS
Transmission scheme	SC, 256 OFDM or 2048 OFDM	SC, 256 OFDM or scalable OFDM with 128, 512, 1024, 2048 subcarriers
Modulation	BPSK, QPSK, QAM16, QAM64	BPSK, QPSK, QAM16, QAM64
Gross data rate	1 – 75 Mbps	1 – 75 Mbps
Multiplexing	TDM/TDMA/OFDMA	TDM/TDMA/OFDMA
Duplexing	TDD, FDD	TDD, FDD
Channel bandwidth	1.25, 1.75, 3.5, 5, 7, 8.75, 10, 14, 15MHz	1.25, 1.75, 3.5, 5, 7, 8.75, 10, 14, 15MHz
WiMAX implementation	256 – OFDM as Fixed WiMAX	Scalable OFDMA as Mobile WiMAX

The primary task of the WiMAX MAC layer [97] is to provide an interface between the higher transport layers and the physical layer. The WiMAX MAC layer is structured in three different sub layers: the security sub layer, the MAC common part sub layer and the service specific convergence sub layer at the uppermost part. The convergence sub layer can interface with a variety of higher-layer protocols, such as ATM, TDM Voice, Ethernet and IP. However, in the meantime, the WiMAX Forum has decided to support only IP and Ethernet due to their predominance. The common-part sub layer of the MAC layer performs all the packet operations that are independent of the higher layers such as fragmentation and concatenation of service data units (SDUs) into MAC packet data units (PDUs), transmission of MAC PDUs, QoS control. The security sub layer is responsible for encryption, authorization, and proper exchange of encryption keys between the BS and the MS.

The purpose of the PHY layer [97] is to deliver information bits from the transmitter to the receiver using the physical medium such as radio frequency, light waves, or copper wires.

Usually, the PHY layer is not informed of quality of service (QoS) requirements and is not aware of the nature of the application, such as VoIP, HTTP, or FTP. The PHY layer can be viewed as a pipe responsible for information exchange over a single link between a transmitter and a receiver.

The IEEE 802.16-2004 standard specified OFDM as the transmission method for NLOS connections. The OFDM signal is made up of many orthogonal carriers, and each individual carrier is digitally modulated with a relatively slow bit rate. This method has distinct advantages in multipath propagation, since for a single carrier transmission method at the same rate more time is needed to transmit a symbol. In case of OFDM modulation used in the 802.16 standard, the bandwidth is divided into 256 subcarriers. When pilot and null subcarriers are removed, 192 subcarriers are left for use in carrying useful data. The capacity of each subcarrier depends on the order of the modulation scheme used. WiMAX supports BPSK (1 bit per subcarrier), QPSK (2 bits per subcarrier), 16QAM (4 bits per subcarrier) and 64 QAM (6 bits per subcarrier). The modulation technique is adapted to the specific transmission requirements. Redundant bits are also carried with useful information for purpose of error detection and correction at the receiving side. The ratio of information to redundant bits is called coding rate and may vary from ½ to ¾. From calculated values it is apparent that overhead introduced by the PHY layer is considerable (in most cases more than 50 %) [98].

WiMAX supports very robust data throughput; theoretical maximums could reach approximately 75 Mbps per channel (in a 20 MHz channel using 64QAM ¾ code rate). A number of factors affect transfer rate beyond simple radio capability, one major element being distance from the BS. Also, the RF and physical environment play a strong role in throughput results. The physics of frequency range also plays a powerful role in bandwidth capability. The high frequencies provide greater bandwidths and the shorter coverage. Lower frequencies enjoy much greater range capability, but at a cost of much lower output bandwidth.

IEEE 802.16e-2005 [25, 100, 101, 102, 103] or mobile WiMAX is developed as an amendment to 802.16d to support subscriber stations moving at vehicular speeds up to 120 km/h [104]. Mobile WiMAX realises the convergence of mobile and fixed broadband access in single air interface and network architecture [105]. The IEEE 802.16e PHY layer has been modified to scalable orthogonal frequency division multiple access (SOFDMA) for improved multi-path performance in non-line-of-sight conditions. The combined effort of IEEE 802.16 and the WiMAX Forum help define the end-to-end system solution for a mobile WiMAX network. Mobile WiMAX systems are to offer scalability in both radio access technology and network architecture. This helps in providing flexibility in network deployment options and service offerings. WiMAX networks are designed to support a multiple set of different applications. Some of the features supported by mobile WiMAX include, but not limited to; high data rates, guaranteed Quality of Service (QoS), high scalability, high security and support of high mobility. All these features enable support of different applications like Interactive Gaming, Voice and Video Conferencing, Streaming Media, Instant Messaging & Web Browsing, Media Content Download (Store and Forward) [104].

With the inclusion of multiple input multiple output (MIMO) antenna techniques to the PHY layer, along with flexible sub-channelization schemes, advanced coding and modulation, high data rates can be easily achieved. The mobile WiMAX technology can support peak downlink (DL) data rates up to 63 Mbps per sector and peak uplink (UL) data rates up to 28 Mbps per sector in a 10 MHz channel. QoS is achieved through sub-channelization and MAP-based signalling schemes to provide a flexible mechanism for optimal scheduling of space, frequency and time resources over the air interface on a frame-by-frame basis. To offer scalability, mobile WiMAX technology is designed to be able to scale to work in different channelization from 1.25 to 20 MHz to comply with varied worldwide requirements. Mobile WiMAX supports optimized handover schemes with latencies less than 50 milliseconds to ensure support of real-time applications. This also makes a promising deal to work with vehicular speeds.

The next standardization effort in which the IEEE 802 is involved in is the IEEE 802.16m project which will support the mobility classes and scenarios supported by the IMT-Advanced cellular systems, including high speed vehicular scenario of up to 350km or even up to 500km/h [28, 30]. IEEE 802.16m amends the IEEE 802.16 Wireless MAN-OFDMA specification to provide an advanced air interface. It will be designed to provide significantly improved performance compared to other high rate broadband cellular network systems.

Cellular/LTE: there are a number of different cellular technologies such as, GSM, GPRS, EDGE, UMTS, IS-95, CDMA2000, and EV-DO. GSM is circuit switched network developed by ETSI as a second generation (2G) for cellular networks. It supports data communications at the maximum rate of 9.6 kbps. GSM was then expanded to provide higher data communications via GPRS, 171 kbps, and later EDGE, 384 kbps. The third generation (3G), UMTS, was then introduced by third Generation Partnership Project (3GPP) to succeed GSM. 3G systems, UMTS/HSPA, support even higher data rates of 144 kbps, 384 kbps, and 2 Mbps under high mobility, low mobility, and stationary environments respectively. IS-95 or cdmaOne is a 2G cellular standard developed by Qualcomm. IS-95 is now replaced by CDMA2000 and a 3G system, CDMA2000 1xEvDO. CDMA2000 or 1xRTT provides rates of up to 141 kbps and CDMA2000 1xEvDO (Rev. A) provides 3 Mbps and 1.8 Mbps for down and up links respectively. The given data rates are only theoretical therefore in practice the rates are lower. In [106], the authors have studied the behaviour of 3G, 1xEvDO, in a vehicular environment, by testing for available upload throughput, packet round-trip-times, and loss characteristics. They reported:

- a high average round-trip-times at around 600 ms,
- a number of short-lived disconnections where they could not transmit data, less than 30 s,
- a varying throughput and the peak upload throughput less than 140 kbps and
- no correlation between the vehicle's speed and the achieved throughput, but geographic location is the dominant factor leading to variations.

Long-Term Evolution (LTE) is the new standard, in the evolution of 2G and 3G systems, recently specified by the 3GPP on the way towards fourth-generation mobile. 3GPP radio access network (RAN) working groups started LTE/EPC standardization in December 2004 with a feasibility study for an Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) and for the all IP-based Evolved Packet Core (EPC). LTE employs OFDMA for the RAN downlink and SC-FDMA (Single Carrier Frequency Division Multiple Access) in the uplink.

LTE has desires to performance requirements that rely on physical layer technologies, such as, Orthogonal Frequency Division Multiplexing (OFDM) and Multiple-Input Multiple-Output (MIMO) systems, Smart Antennas to achieve these targets. The main objectives of LTE are to minimize the system and User Equipment (UE) complexities, allow flexible spectrum deployment in existing or new frequency spectrum and to enable co-existence with other 3GPP Radio Access Technologies (RATs). E-UTRA is expected to support different types of services including web browsing, FTP, video streaming, VoIP, online gaming, real time video, push-to-talk and push-to-view. Therefore, LTE is being designed to be a high data rate and low latency system as indicated by the key performance criteria. The bandwidth capability of a UE is expected to be 20MHz for both transmission and reception. Among others, LTE design targets are the following.

- Support for IP-based traffic with end-to-end Quality of service (QoS).
- The system should support peak data rates of 100 Mbps in downlink and 50Mbps in uplink within a 20MHz bandwidth
- Reduced latency to 10 ms
- Support mobility of up to 350 km/h.
- Operation in both TDD (unpaired) and FDD (paired) spectrum modes.
- Spectrum flexibility, seamless coexistence with previous technologies, GSM/EDGE/UMTS, systems and reduced complexity and cost of the overall system.
- Supports hand-over and roaming to existing mobile networks giving the service providers the ability to deliver a seamless mobility experience.

2.6 Approaches in Literature Survey

The most adopted vehicular networking architectures consist of road-side units (RSUs) existing along the road and vehicle equipment called an on board unit (OBU) and application units (AUs) executing a single or a set of applications. OBUs and RSUs form ad hoc networks where communication takes place directly between OBUs via multi-hop or single-hop (called V2V), or in which OBUs communicate with RSUs in order to connect to external networks or infrastructure (called V2R or V2I) and where OBUs communicate with the RSUs through other OBUs (called V2V2I) [4, 107, 108, 109, 35].

In [110], Tufail et al. studied the behaviour of network connections that are initiated over an IEEE 802.11g channel from a moving car. The goal was to investigate and discuss the possibility of using IEEE 802.11 as the protocol to establish connection between fast moving vehicles and to understand the impact of the vehicle's speed. The experiment involved measuring the amount of data transferred during the short spurts the connection was intact. This involved two vehicles travelling in opposite directions keeping the speed constant for a single trial but varying speed from trial to trial. The laptops were configured to operate in ad-hoc mode and no external antennas were used. The results showed that the vehicle speed has an impact on the data rate and connection duration (contact time). As the vehicle speed increases the intact time decreases so does the data rate hence less data can be transferred. They achieved a peak data rate of 7.7 Mbps at the speed of 20mph or 32km/h (relative speed of 40mph or 64km/h) and managed to transfer 15.1MB. At the speed of 60mph or 96km/h (relative speed of 120mph or 193km/h), it was possible to transfer 0.3MB of data and maintain a data rate of about 1 Mbps.

Marcelo et al. [3] had a test-bed similar to [110]. They investigated the characteristics of links formed by in-car nodes running off-the-shelf wireless technologies. The two wireless technologies were IEEE 802.11a and IEEE 802.11g and were configured to operate in ad hoc mode. They also included the impact of transport protocols (TCP and UDP) and packet size on the amount of data transferred. The car speed was varied from 20km/h to 60km/h (relative speed of 40km/h to 120km/h), while the packet sizes tested were 150, 500 and 1460 bytes for both TCP and UDP. The results show that using TCP instead of UDP reduces the average total amount of data transferred, and as speed increased no data was received due to the long time TCP spends trying to establish a connection. They also showed that higher frequency 5.15GHz IEEE 802.11a is more prone to propagation problems (diffraction, reflection, and absorption) than lower frequency IEEE 802.11g which lead to shorter contact time. Again they showed a trade-off between speed and packet size; decreasing the packet size reduced the capacity loss and increased the capacity as speed increased.

Wellens et al. [111] investigated the one hop performance of IEEE 802.11a/b/g for car to car (C2C) and car to roadside (C2R) scenarios. They had one node operating as an access point (AP) while the other was in normal configuration. For C2R measurements they placed the AP in the middle of a 2km road while a car connects to it as it passes by. The external antennas with 5 dBi gain were used to provide line of sight. Both UDP and TCP traffic with different packet sizes were generated to evaluate their effect at vehicular speeds and these were compared with the static measurement values performed in the lab where the distance between AP and client node was 1m. The tests were conducted under urban scenario with the presence of traffic and tall buildings and on a highway. Throughput, signal to noise ratio (SNR) and frame error rate were tracked in these experiments. They found throughput at 120km/h to be slightly lower than that of static case and larger packets presented a worse reception compared to smaller packets. The communication range was also found to be larger when using lower physical layer rates due to the use of less aggressive coding and modulation schemes. Speed did not affect the performance of Wi-Fi but distance and availability of line of site did create a negative impact.

Chou et al. [112] studied the feasibility of using fixed WiMAX (IEEE 802.16d) for V2I communication in comparison with Wi-Fi (IEEE 802.11g). The measurements focused on throughput, latency and packet loss. For WiMAX two modulation modes, BPSK ½ and 64QAM ¾ were studied. They found that even though they managed to achieve data transfers at long ranges with WiMAX, with Wi-Fi one can get higher throughput and a shorter latency at shorter distances. Frame duration also seemed to be a major factor in WiMAX; as the frame duration increased, round trip time also increased hence increasing latency. They also found that larger frame sizes offer better throughput but at a cost of longer delays hence they are more suitable for delay tolerant applications. The same study was conducted on QualNet 4.5 simulation tool by Msadaa et al. [113] but instead they used IEEE 802.11p and mobile WiMAX (IEEE 802.16e). They evaluated the performance for different vehicle speed, data rates and network deployments. They also showed that mobile WiMAX suffers longer delays compared to IEEE 802.11p and the average throughput does not depend on the vehicle speed.

Miller [4] presented a V2V2I architecture which combines V2V and V2I architectures whereby vehicles form zones and one is selected as a super node using a proposed super vehicle detection algorithm. The super node collects data from vehicle in its zone and sends it to the roadside server. The analysis is performed using a FreeSim simulation tool. The same approach is performed by Benslimane et al. [114] where they proposed and simulated on NS2 an integrated VANET - 3G network architecture where they created dynamic vehicle clusters. Within each cluster all vehicles were equipped with IEEE 802.11p interfaces while some vehicles were equipped with extra UTRAN interfaces to act as gateways to link VANET to UMTS. Gateway selection and clustering are performed based on route stability, mobility and signal strength through a proposed dynamic clustering and gateway management algorithms implemented on top of routing protocol. The aim was to reduce frequent handoffs at base stations and decrease bottlenecks and congestion across path towards a gateway; also to allow vehicles without 3G to access UMTS network. They evaluated the performance based on data packet delivery ratio, throughput, packet drop and delay. They implemented their proposed algorithm on top of AODV protocol in comparison with Multi-metric Gateway Selection Algorithm (MGSA). They achieved better data packet delivery ratios and higher throughput in comparison.

J. Eriksson et al. [115] designed, implemented and experimented evaluation of Cabernet Transport Protocol (CTP), a content delivery network for vehicles moving in and around cities. Cabernet delivers data to and from cars using open IEEE 802.11b/g access points (APs) that the cars connect to opportunistically while they pass by. The primary goal of CTP was to develop techniques that allow moving cars to obtain high data transfer throughput through these APs. The system was deployed in 10 taxis running in the Boston area. The nodes/vehicles were running QuickWiFi and the system running CTP. QuickWiFi was used to reduce connection establishment time. They showed that QuickWiFi was able to connect in 366 ms on average. Also shown was the ability of CTP to achieve double the throughput of TCP over paths with high non-congestion losses with a mean throughput of 800 kbps when connectivity is present and in an end-to-end performance evaluation, Cabernet was able to achieve an end-to-end throughput of 38 megabytes/hour (86.5 kbps) per car during its drive.

M. Aguado et al. [104] presented a mobile WiMAX network deployment as a candidate for broadband and low latency V2I communication architecture. The authors presented and evaluated the performance of a mobile WiMAX network architecture deployment in two highly demanding V2I scenarios;

i the two mobile nodes supporting real-time applications crossing during handover case varying their speeds from 100 km/h to 160 km/h and
ii a heavy loaded scenario with forty (40) mobile nodes initially attached to the same base station and support the same real time application with the traffic centre.

The evaluation scenario was built using the Opnet Beta WiMAX model (Feb 2008 release). For the first test, they showed a drop in the data traffic when the two mobile nodes cross each other during the handover process. They also showed that it is possible in some cases that handover is higher than the expected 50ms delay value but the number of these events is low and does not compromise the average value obtained. As for the second test, the end-to-end delay increases but still met the WiMAX radio system profile requirements.

Chapter 3 Experimental Setup

This work evaluates a system that uses a combination of WiMAX and Wi-Fi to respectively provide V2I and V2V connectivity in a V2V2I vehicular network. To ensure the validity of vehicular network, a proper data exchange between node members of a network requires, among other characteristics, the inclusion of node mobility under different environmental conditions. The experiment consists of two vehicles (mobile nodes) that are linked with an ad-hoc Wi-Fi connection and a stationary base station with a dedicated WiMAX connection to one of the vehicles. Wi-Fi ad-hoc mode allows the devices to communicate with each other without the use of access point (AP), and all devices in range connect in a peer-to-peer fashion. WiMAX was chosen because the wide coverage it offers and Wi-Fi because of its availability and resemblance to the upcoming IEEE 802.11p standard developed specially for use in VANETs.

The experimental setup was designed to accurately reflect conditions present in an urbanised environment. In a real world scenario, vehicles come in contact with each other in different ways, by moving either perpendicular or parallel to each other [116]. The perpendicular movement can happen when both vehicles approach or leave an intersection and when one vehicle approaches while the other leaves an intersection. The parallel movement happens when vehicles travel in the same direction following each other or when they travel in opposite direction to each other. In all these cases the contact time is either long lived or short lived. These scenarios are represented in this research, the long lived contact, by allowing vehicles to travel in the same direction following each other, and the short lived contact by travelling in opposite directions. This helps in determining the kind of applications that can be supported as it gives an indication of how much data can be transferred in the best and worst case scenarios.

Since the experiment concurrently uses two different wireless technologies (Wi-Fi and WiMAX), initial tests were performed to characterise the individual performance of each technology before combining the two. This approach ensures that each part of the system is functional before integrating the full experiment, but also provides clues as to how each of the components impact system performance. Therefore Wi-Fi and WiMAX performance were first evaluated separately. The experiment was then divided into four sets:

(i) vehicle-to-roadside communication architecture, V2R, using Wi-Fi,
(ii) vehicle-to-vehicle communication architecture, V2V, also using Wi-Fi,
(iii) vehicle-to-infrastructure communication architecture, V2I, using WiMAX and,
(iv) vehicle-to-vehicle-to-infrastructure communication architecture, using Wi-Fi and WiMAX.

The first set of experiments was conducted separately from others on an open space outside Stellenbosch University campus where there is less traffic and signal interference is low, as illustrated by Figure 3.1. The IEEE 802.11g was used on this route and the communication range was found to be around 180 m. This was determined by fixing the roadside node at the centre of the road (point X) and slowly moving the mobile node away and towards it. When moving away and or towards the fixed node, the positions where the link was lost and established were respectively marked, providing the communication range. The procedure was repeated on either sides of the fixed node. Therefore the start/end of communication range were marked point A and B. These points were then chosen to be approximately 400 m apart, allowing the stationary node, point X, to be placed 200 m from each point, well off the communication range.

Figure 3.1. Open space for V2R experiments using Wi-Fi (802.11g)

The other three sets of experiments (two to four) were carried out on the University campus on two routes within range of the WiMAX Base Station (BS). The first route in campus is close to the BS with direct line of sight (LOS) of the BS, while the second route is further from the BS in town centre, a built environment representing non line of sight (NLOS), illustrated in Figure 3.2. Here IEEE 802.11n was used for the V2V, and in the same way as in the first experimental setup, the communication range was found to be around 300 m hence the start and end points were placed over 400 m.

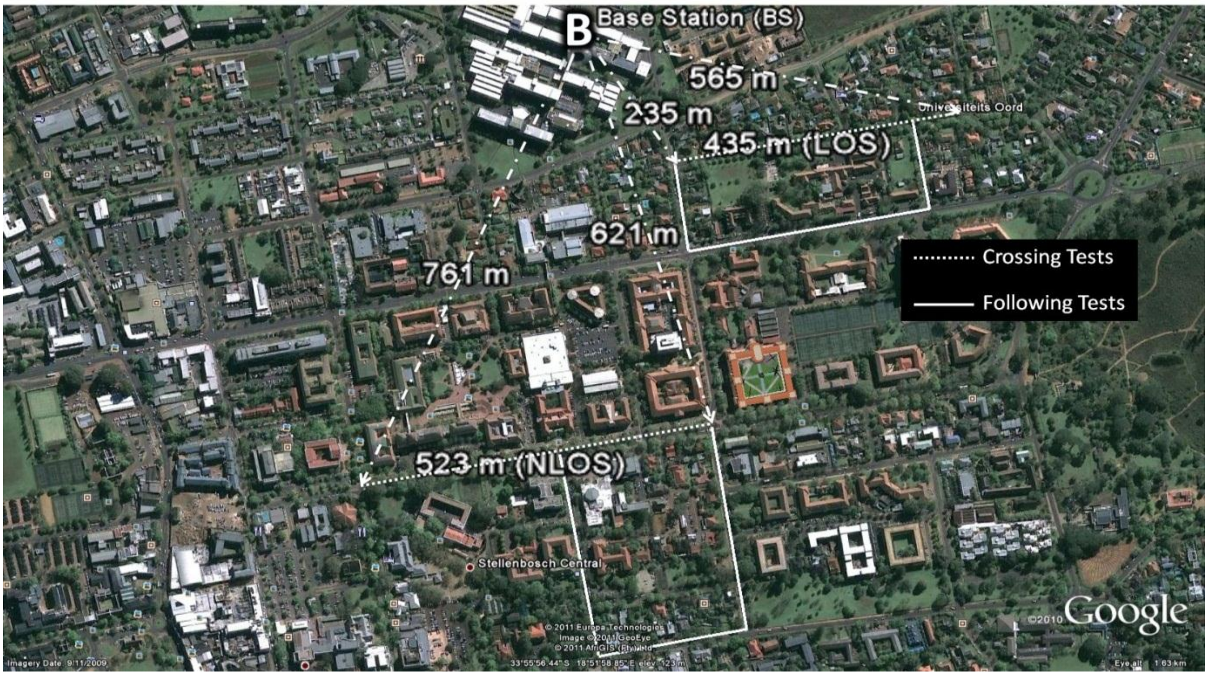


Figure 3.2. Area where V2V2I experiments were conducted in Stellenbosch Campus

3.1 Used Equipment and Configuration

Our experiments were carried out using off-shelf equipment. The vehicle to roadside, V2R, network was built using two Wi-Fi enabled laptops. The first laptop being a HP Pavilion dv6000 using wireless NIC Broadcom BCM4311 802.11b/g, running Windows Vista OS while the second laptop was a Lenovo T400 using wireless NIC ThinkPad 11b/g Wireless LAN Mini PCI Express running Windows XP professional OS.

The V2V, V2I and V2V2I networks were also built with two laptops, namely, a Lenovo T400 and a Gigabyte M1022C, both running Microsoft Windows XP Professional. The built-in Wi-Fi adapters for the laptops were turned off and external Wi-Fi adapters were used. The adapters were mounted outside the vehicles to increase coverage. The WiMAX subscriber unit (SU) was placed in one of the vehicles and a WiMAX base station was mounted on top of a five storey building (indicated with B in Figure 3.2). In addition both the vehicles were equipped with GPS dongles to monitor the position and speed of the vehicles.

Speed (absolute and relative vehicle speed), separation (between vehicles and from BS), signal strength (WiMAX and Wi-Fi), modulation type (WiMAX and Wi-Fi), throughput, data transferred, contact time (time from first packet to last packet received) and jitter were recorded for each of the experiments conducted. Speed and position were recorded on each node while the Wi-Fi RSSI and modulation type, throughput, data transferred, jitter and contact time were recorded on the server node. The WiMAX RSSI and modulation type were recorded on the base station's PC. Table 4 provides a list of what was logged and calculated with respect to different VANET architectures.

Table 4. Results logged and calculated for each communication architecture

			V2V		V2I		V2V2I			
			Following	Crossing	LOS	NLOS	Following		Crossing	
							LOS	NLOS	LOS	NLOS
Logged	Position (Coordinates)		√	√	√	√	√	√	√	√
	Absolute Speed		√	√	√	√	√	√	√	√
	RSSI	Wi-Fi	√	√	-	-	√	√	√	√
		WiMAX	-	-	√	√	√	√	√	√
	Throughput	Wi-Fi	√	√	-	-	√	√	√	√
		WiMAX	-	-	√	√				
	Data Transferred		√	√	√	√	√	√	√	√
	Jitter		√	√	√	√	√	√	√	√
Calculated	Separation	Vehicles	√	√	-	-	√	√	√	√
		BS	-	-	√	√	√	√	√	√
	Relative Speed		-	√	-	-	-	-	√	√
	Cumulative Data Transferred		√	√	√	√	√	√	√	√
	Contact Time		√	√	√	√	√	√	√	√

3.1.1 Wi-Fi Configuration

Wi-Fi ad-hoc network or Independent Basic Service Set (IBSS) was used in this setup because future vehicular networks are expected to operate in this fashion. In this mode the devices communicate directly with each other in a peer-to-peer fashion. The major setback in ad-hoc mode is, as the number of devices grows the performance of the network decreases. But for this experiment only two nodes are allowed to communicate. All the wireless adapters in an ad-hoc network are expected to use the same SSID and channel number. Because Wi-Fi operates on an unlicensed frequency band of 2.4GHz it is likely to get interference not only from other Wi-Fi devices but from other devices like Bluetooth, TV remote controls, which also use the same frequency band. But with a careful configuration, the overall interference can be minimised. In this experiment channel 1 was selected mainly because it has the least number of channels (other Wi-Fi channels) interfering with it: the lower the interference the higher the throughput hence improved system performance.

To reduce connection time and speed up data exchange, the use of static IP address was employed while open authentication was used and allowed to send unencrypted data. The transmit power in our system was set to automatic to incorporate mobility, allowing the devices to adjust the power levels accordingly based on the distance between the nodes.

In [3] the authors showed that when compared to IEEE 802.11g, IEEE 802.11a gives a poor performance. The overall transmission range was shorter leading to short contact time and less data successfully transferred. For this reason, in this research IEEE 802.11g was selected for V2R communication architecture, where the laptops' built-in Wi-Fi cards were used. On the other hand, to increase the communication range, in the V2V and V2V2I communication architectures, the built-in WLAN devices were switched off on both laptops. Instead EDiMAX EW-7711USn USB adapters [117] with omnidirectional 3dBi gain detachable antennas were used. This Wi-Fi adapter supports the IEEE 802.11b/g/n standards. In this part of experiment IEEE 802.11n was chosen for its higher data rates. The Windows wireless zero configuration utility was also disabled and Edimax wireless configuration utility, EZmax, was used to control and configure the wireless adapter. The configuration parameters used for Wi-Fi are shown in Table 5.

Table 5. Wi-Fi configurations

Standard	IEEE 802.11g	IEEE 802.11n
Network Type	Ad hoc	Ad hoc
Channel	1	3
Authentication	Open	Open
Encryption	None	None
Frequency Band	2.4000~2.497GHz	2.4000~2.4835GHz
Link Speed	5.5Mbps	54Mbps
Modulation	DSSS/CCK	OFDM
Transmit Power	Auto	Auto

3.1.2 WiMAX Configuration

For the WiMAX link, Alvarion BreezeMax TDD Micro Base Station (BS) and a BreezeMax Si 1000 CPE were used [118]. The self-install (Si) CPE is a compact plug-and-play unit designed for indoor use and utilises the Intel PRO/Wireless 5116 broadband interface chip. The CPE has an integrated internal array of six antenna elements with a fast bi-directional switching matrix providing full 360° coverage. The bi-directional switching matrix allows using either the same or different antennas for transmit and receive. The CPE was connected to the laptop through the 10/100 base T port. It supports BPSK, QPSK, 16QAM, 64QAM modulation techniques with 1/2, 2/3, 3/4 coding. The quality of the uplink (UL) and downlink (DL) is continuously monitored to control the modulation and coding schemes. The BS selects a modulation technique using multi-rate algorithm using the link quality information such as multipath, Burst Error Rate (BER) and Signal to Noise Ratio (SNR), received from the SU. The modulation technique can change on a per frame basis. The BS and SU comply with the IEEE 802.16d standard operating at 2.5GHz band and uses time division duplexing (TDD) with a channel bandwidth of 5MHz. TDD offers the ability to adjust the DL and UL ratio, and it was set to 50/50 (UL/DL). The BS and SU specifications and configurations are shown in Table 6.

Table 6. IEEE 802.16-2004 (Fixed WiMAX) configurations

Frequency Band	2.496 – 2.690 GHz
Transmission Scheme	256 OFDM
Modulation	Downlink: OFDM, Uplink: OFDMA-16 BPSK, QPSK, QAM16, QAM64
FEC	Convolutional Coding: ½, 2/3, ¾
Operation Duplex Mode	TDD
Duplex UL/DL Ratio (%)	50/50
Channel Bandwidth	5MHz
Transmit Power	Auto
Antenna Height (m)	30

3.1.3 Network Monitoring Tools

The network performance was monitored with Iperf [119] which uses a client server approach, whereby one node sends network traffic (client) and the other node receives the network traffic (server). For V2V communication one of the nodes ran Iperf in a server mode while the other in a client mode. For V2I communication a node acted as a server while a PC with a LAN connection to the WiMAX BS acted as a client. For the complete V2V2I communication we had the same configuration as in V2I communication except the server node was now connected to the bridge node using Wi-Fi. In all the cases, UDP traffic was generated using Iperf, which also measures throughput, data transferred and jitter. A script was used to read and record the received signal strength indicator (RSSI) reported by the Wi-Fi card driver from one of the laptops. Another script on a PC at the BS was used to record the WiMAX RSSI reported by the BS access unit. The Iperf default settings were adopted where the client periodically sends 1470byte UDP datagram to the server. Net meter [120], a network traffic monitor, was used to verify the results reported by Iperf.

The UDP protocol was chosen because of the inability of the TCP protocol to efficiently manage the effects of mobility in mobile ad hoc networks [121, 122, 123, 124, 125, 126, 127]. Station movements may cause route failures and route changes and, hence, packet losses and delayed ACKs. The TCP misinterprets these events as congestion signals and activates the congestion control mechanism. These lead to unnecessary retransmissions and throughput degradation. In addition, node mobility may aggravate the unfairness between competitive TCP sessions [128].

3.2 Experimental Approach

3.2.1 Wi-Fi Only Tests (V2R and V2V)

For Wi-Fi only communication (V2V), three tests were carried out:

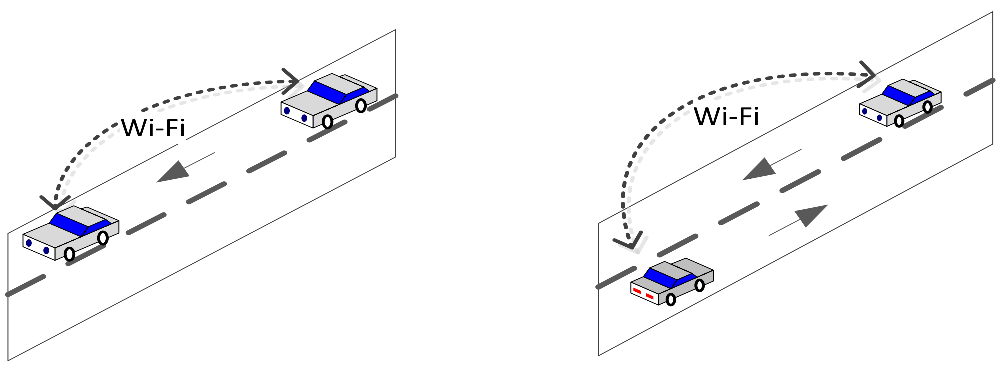
(i) vehicles following each other on the routes,

(ii) vehicles crossing each other (from opposite directions) on the routes, and

(iii) vehicle sending/receiving data to/from a stationary node on a roadside.

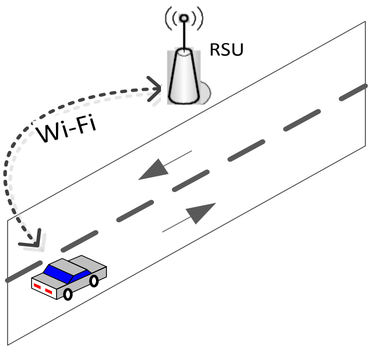
The tests are depicted in Figure 3.3 (a), (b) and (c) respectively. For V2R experiments, to investigate the effect of node mobility on Wi-Fi, different relative vehicle speeds were considered; 40 km/h, 50 km/h, 60 km/h, 80 km/h and 90 km/h. Because the effect of mobility is of interest here, keeping the vehicle speed constant while in range was crucial to allow for easy calculation of relative speed. Hence it was made sure that when the node reaches either starting or ending point (point A or B in Figure 3.1), the node is already at the required speed until it reached the other point.

Knowing the behaviour of Wi-Fi under different vehicular speeds (from V2R experiments), V2V looked at how much data can be transferred using Wi-Fi at different vehicular behaviours under different environmental conditions. Here the individual vehicle speed was kept below the legal speed limit of 60 km/h. An additional test was also performed where the two vehicles were following each other for 50 km on a highway route with speeds up to 120km/h and the separation kept below about 100 metres.



(a) V2V vehicles following

(b) V2V vehicles crossing



(c) Vehicle and a Roadside Unit (RSU)

Figure 3.3. Initial V2V performance tests using Wi-Fi

3.2.2 WiMAX Only Tests (V2I)

For WiMAX only communication (V2I), the WiMAX enabled vehicle was driven along both routes, Figure 3.4. This enabled us to seamlessly integrate the two technologies and test with one of the nodes configured as a network bridge connected to the other node using Wi-Fi and to the infrastructure (BS) using WiMAX.

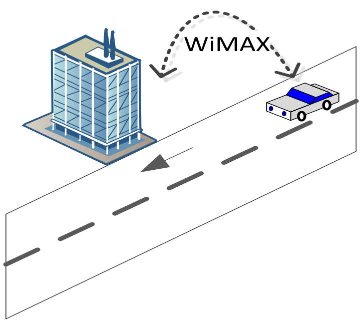
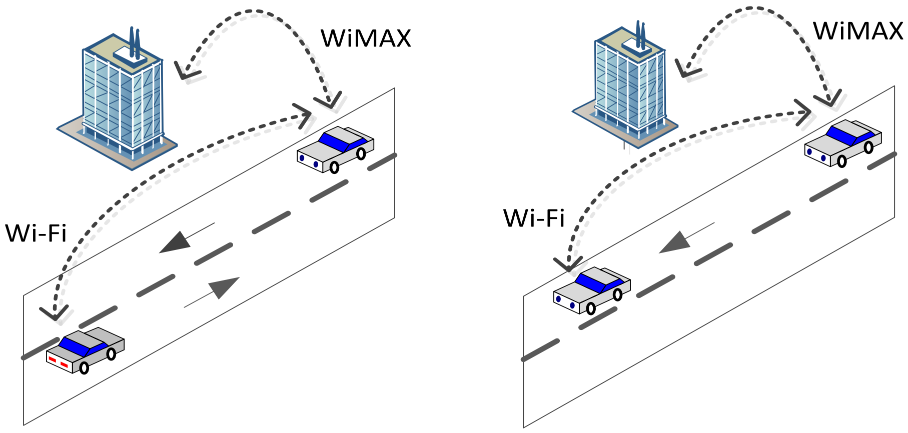


Figure 3.4. V2I performance tests using WiMAX

3.2.3 Wi-Fi and WiMAX (V2V2I)

For the complete experiment using V2V2I communication, the two tests, following and crossing, were repeated on both routes as shown in Figure 3.5.



(a) V2V2I setup for vehicles crossing (b) V2V2I setup for vehicles following

Figure 3.5. V2V2I tests using combination of Wi-Fi and WiMAX

3.2.4 Live Audio and Video Streaming

In addition to the quantitative link performance results, the V2I and V2V2I configuration was also used to qualitatively evaluate the link using video and audio streaming from the base station to both vehicles. A live video from a TV channel was streamed over WiMAX using an open source multimedia player called videoLAN (VLC). VLC was configured to stream the video in H.264/AVI or MPEG-4 encoding format and the audio stream was encoded in AAC. The video bit rate configuration was 300 kbps, 15 fps and the audio bit rate was 96 kbps.

Chapter 4 Results and Discussion

In this research we evaluated the performance of Wi-Fi (IEEE 802.11 g/n) and WiMAX (IEEE 802.16d) for different VANET architectures based on measurements of contact time, throughput/data rate, received signal strength, jitter, and total data transferred. Signal strength, herein referred to as received signal strength indicator (RSSI) is measured in decibels given in relation to one milliwatt (dBm). Throughput is a measure of the amount of packets that can be transmitted at a given amount of time measured in kilobits per second (kbps) or Megabits per second (Mbps). Jitter is the delay variation in packets measured in milliseconds (ms) and total data transferred represents the data bytes (B) that are correctly received on the server side and with an acknowledgment correctly received on the client.

Line-of-sight (LOS) was always maintained for pure V2V communication because of the usage of short range Wi-Fi, while V2I communication was operated under LOS as well as non-LOS (NLOS) conditions. V2V2I communication utilised both Wi-Fi and WiMAX hence it also operated under LOS and NLOS conditions. When this paper refers to LOS and NLOS we therefore refer to WiMAX line-of-sight or non-line-of-sight.

The experimental results are graphically presented on time based plots, with time increasing to the right. In order to capture significance of physical separation, the labels presented on the horizontal axes are separation at the time, rather than the time.

4.1 Vehicle to Roadside (Wi-Fi - IEEE802.11g)

Figure 4.1 shows the measured throughput as a function of distance from the results obtained when a car was moving at 60km/h. As the mobile node approaches or leaves the stationary node, throughput rapidly increases and decreases respectively at around a range of 100 m and the peak throughput is reached within that radius. This change is also visible in Figure 4.2 where the signal strength begins to increase from the same range of around 100m. Also visible from the figures is even when the two nodes are crossing each other; the throughput and the signal strength seem to drop slightly. This behaviour is caused by the power management techniques [24]. As the nodes approach each other, they tend to decrease the transmission power, and as they separate they increase the power to try and keep the connection until the maximum power level is reached and the link is lost.

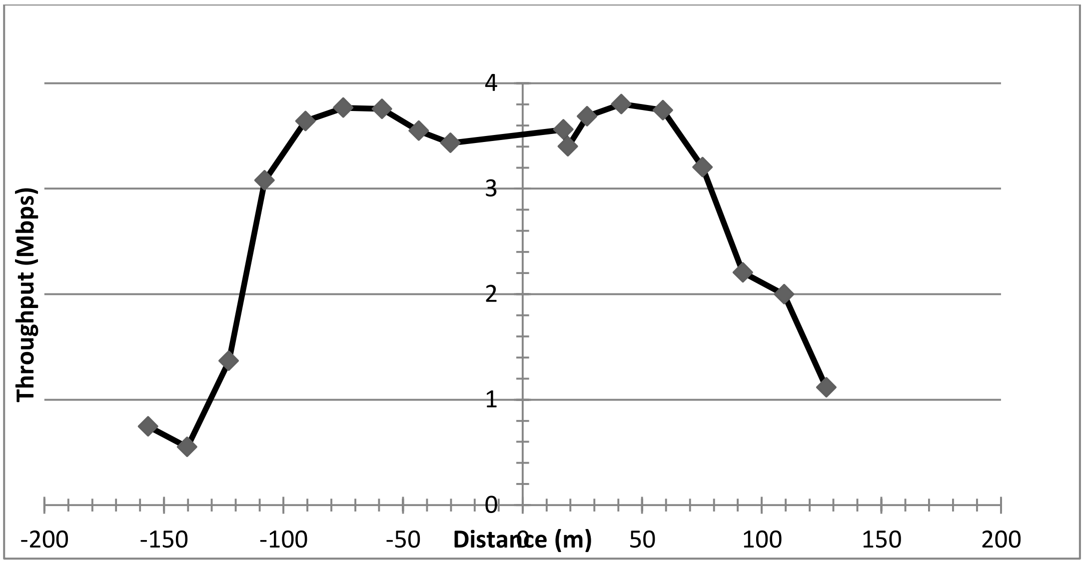


Figure 4.1. Average throughput as the car travels at 60km/h

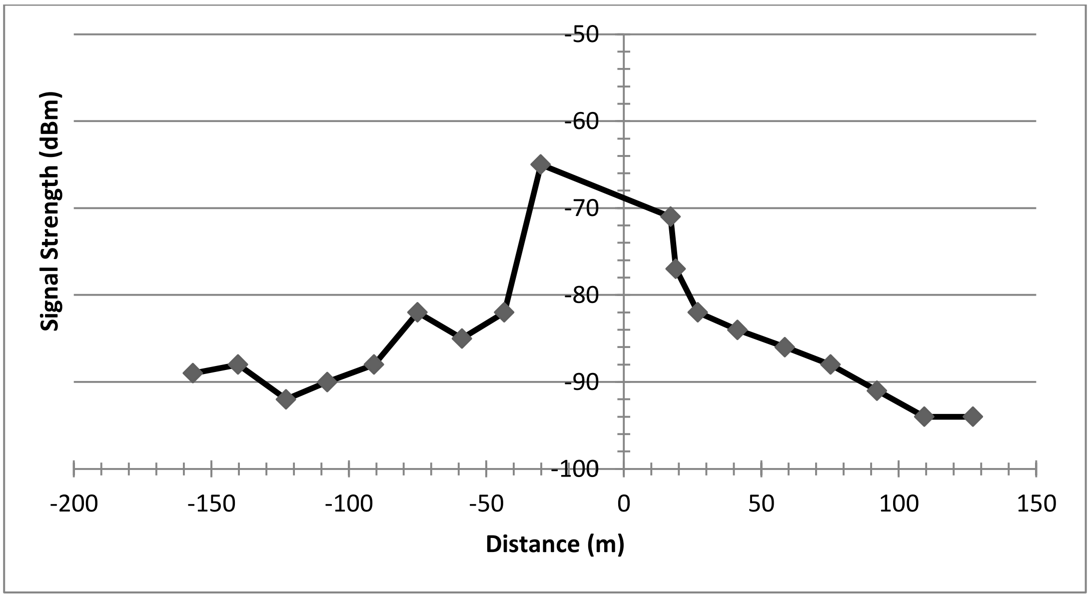


Figure 4.2. Average signal strength as the car travels at 60km/h

Figure 4.3 shows the average total data transferred, average throughput and average contact time (time taken for a connection) between the two nodes while moving at different speeds. From the graph, it can be seen that as the speed increases, as expected the connection time decreases hence also a decrease in total data transferred. The interesting part to be noted here is the behaviour of the throughput; it does not follow the node's speed. As an example, the throughput when the speed is 40 km/h is lower than when the speed is 60 km/h and even lower at 90 km/h hence showing it does not increase or decrease with speed. This goes in-line with the conclusion in [24], namely that one of the requirements of IEEE 802.11 is to support both mobile as well as portable stations. It is further explained that since each RF component follows its own distinct path, there will be differences in travel times and RF wave geometry; initially a uniform RF wave leaves the transmitting antenna, as the wave traverses space, it may encounter obstacles that alter the original wave or create new RF signals. One or more components of the original RF wave may continue travelling straight to the receiving antenna; other components may diffract, scatter, or reflect off of obstructions. These propagation effects blur the distinction between portable and mobile stations making stationary stations to often appear to be mobile.

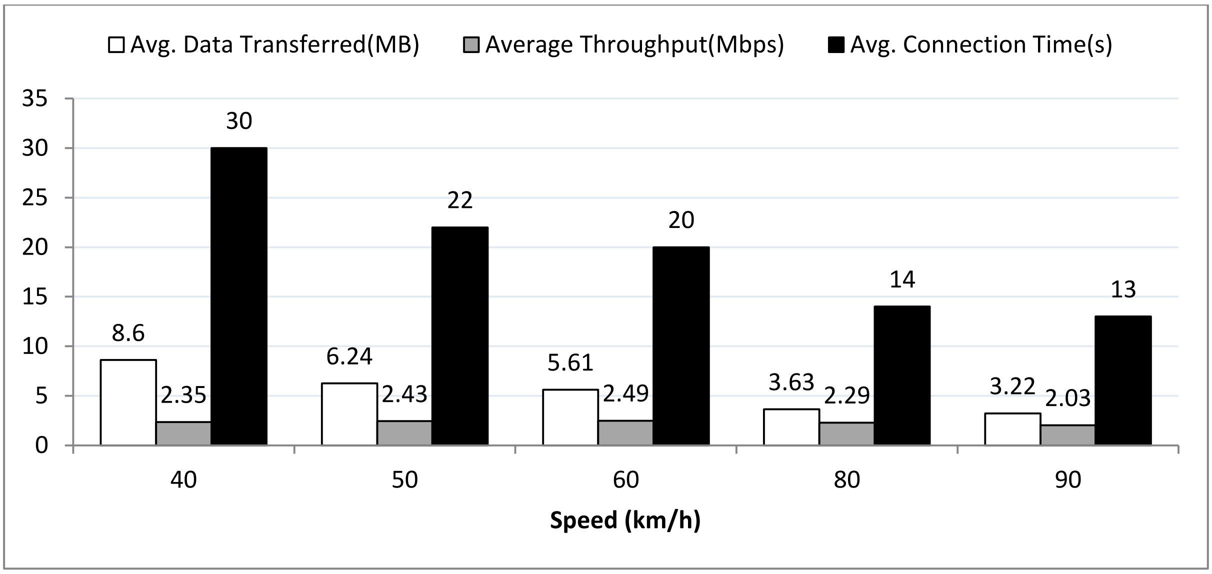


Figure 4.3. Overall performance of IEEE 802.11g in V2R at vehicular speeds

Figure 4.4 shows a plot of the signal strength for all the tests performed at different vehicular speeds. Again the signal strength on all the cases does not change with speed, but rather with the separation of the nodes. Figure 4.5 shows a plot of throughput as speed changes. The throughput behaviour, as expected, follows that of the signal strength whereby the data is transmitted when the two nodes are in range. Again as the signal gets stronger the throughput also increases.

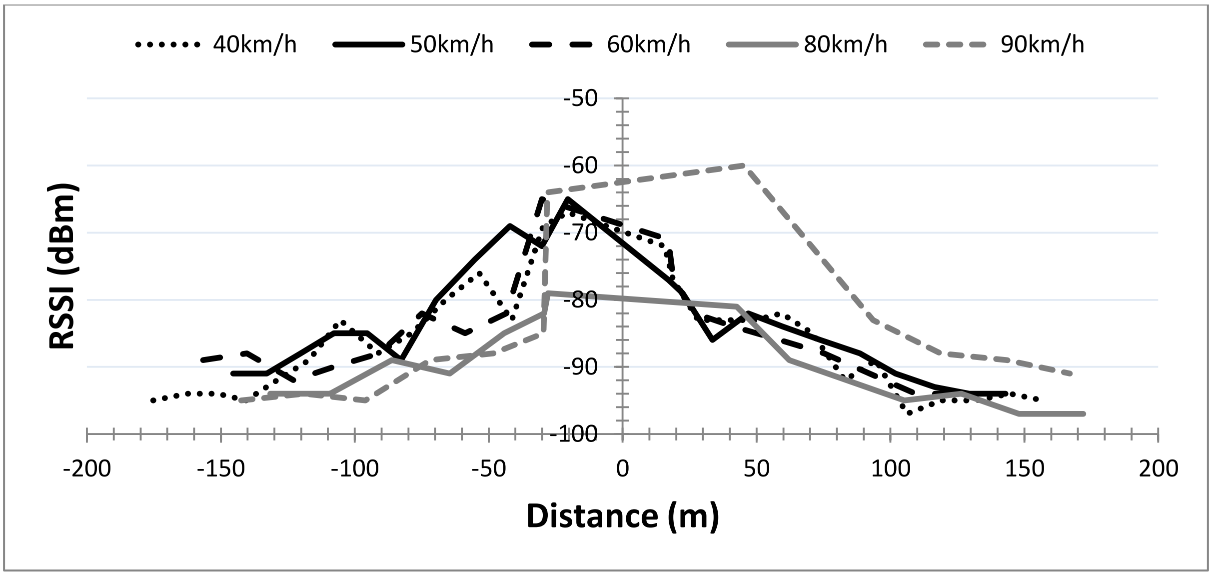


Figure 4.4. Signal strength received for different vehicular speeds

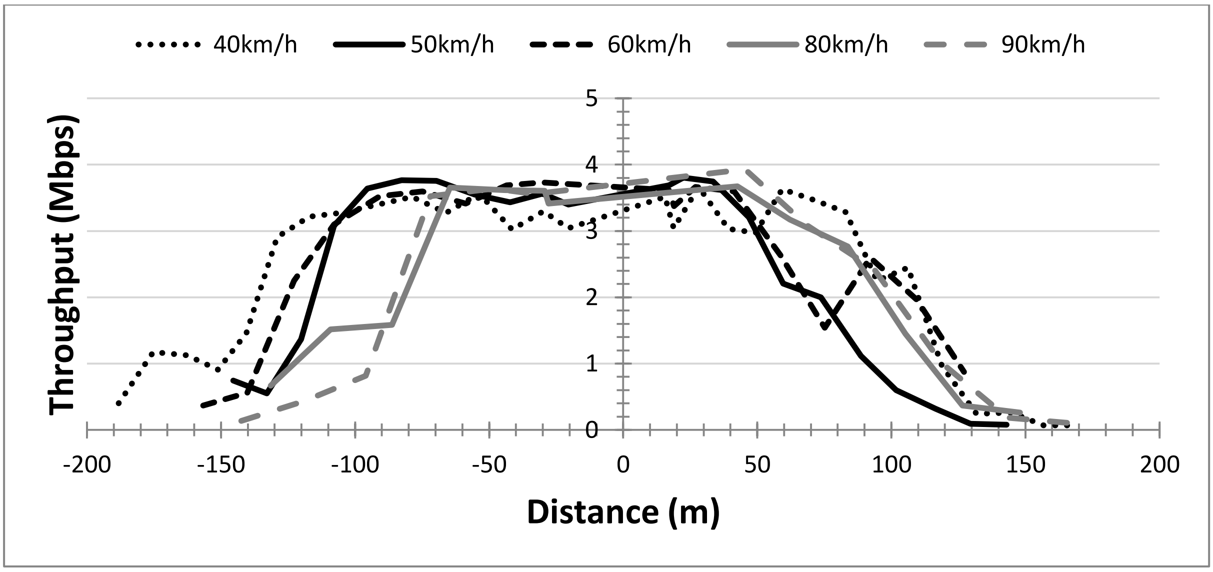


Figure 4.5. Throughput measured for different vehicular speeds

4.2 Vehicle to Vehicle communication (Wi-Fi - IEEE802.11n)

4.2.1 Vehicles following each other

Figure 4.6 shows, for a representative 100 s, the throughput and signal strength with respect to separation (on time-based axis) between the two vehicles following each other. The test was conducted on a highway with a measured average absolute vehicle speed of 113 km/h. The average results recorded for the tests are separation of 34 m, throughput of 31.3

Mbps, and average jitter of 0.38 ms. A total of 386.3 MB of data was transferred in a 100 seconds period. The maximum peak data rate recorded was 34.5Mbps occurring at random points in the test. For the full test, which lasted 20 minutes, 4.4 GB were transmitted from one car to the other. The similar results were obtained when the setup was conducted in an urban environment.

At various stages of the experiment there were obstacles (other vehicles) in-between the two communicating vehicles. This is visible from the graph where the throughput increases and decreases sharply. Since the radio was set to automatically adjust the transmit power, the radio would automatically adjust the power level when the link became weak. The variation in signal strength was therefore additionally affected by the increase in transmission power of the Wi-Fi card.

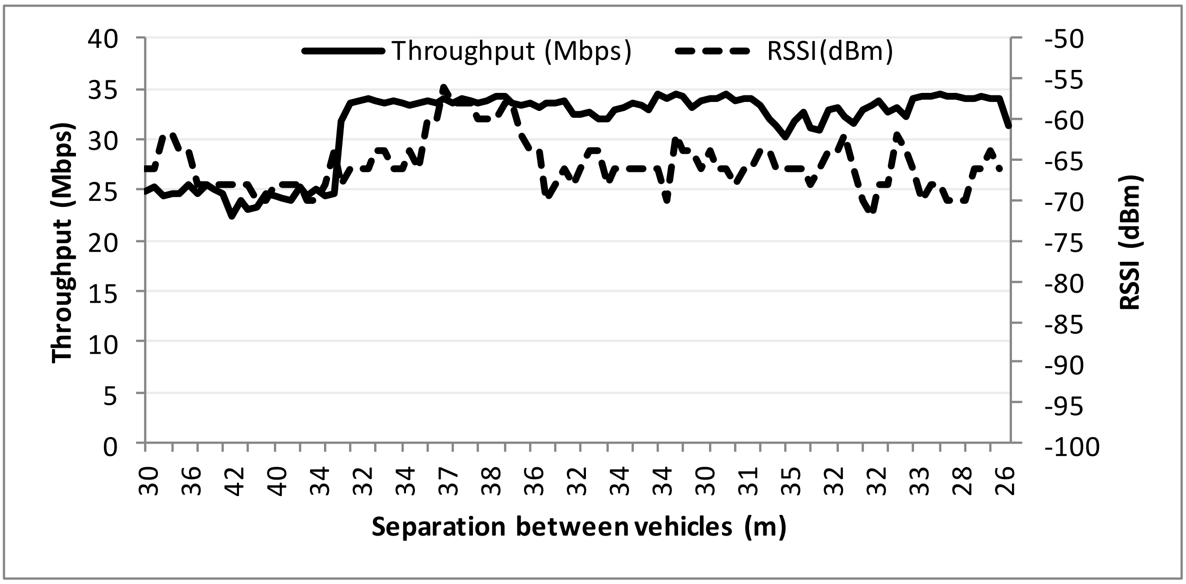


Figure 4.6. V2V communication for vehicles following

4.2.2 Vehicles moving in opposite directions

Figure 4.7 shows a graph of the two vehicles travelling in opposite directions at an average relative speed of 64 km/h in an urban area. The average contact time recorded was 33 s and the average communication range was found to be 302 m with an average throughput of 13.7 Mbps per test run taken over the period of established contact, average jitter of 1.88 ms and an average of 51.7 MB data transferred. The maximum peak data rate of 31.7 Mbps was reached with the vehicles 0 m from each other i.e. at the point of crossing. The plot shows the throughput and signal strength with respect to separation between the two vehicles.

From the figure, the Wi-Fi's data rate seems to indicate a dependence on signal strength which is in turn affected by the separation between the two vehicles. The same behaviour is also reported in [3, 111, 112], as the two communicating nodes come closer, the signal strength increases, and so does the data rate.

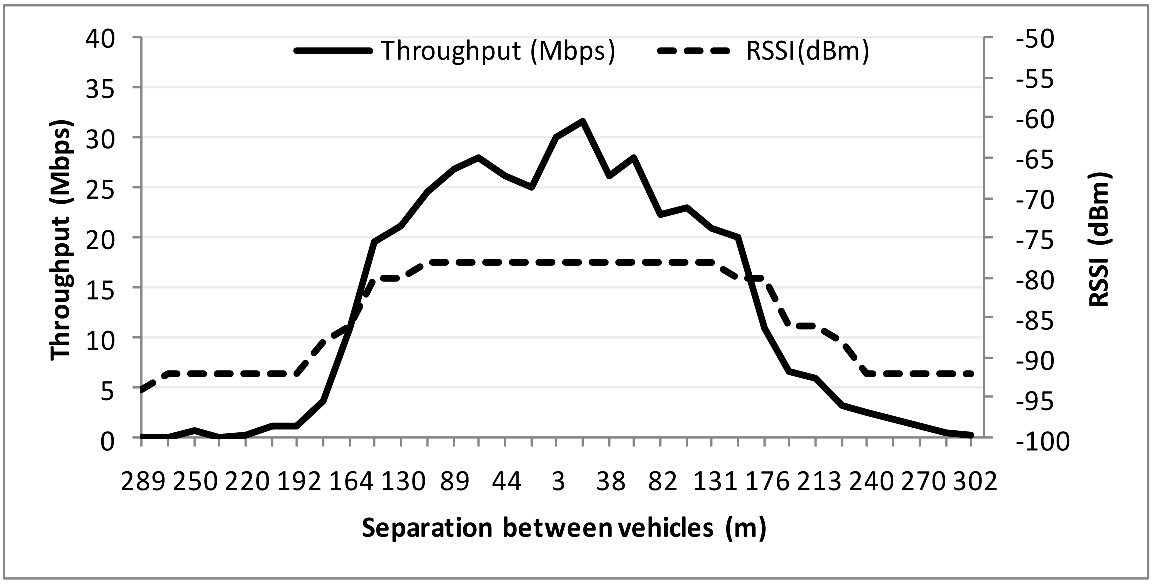


Figure 4.7. V2V communication for vehicles crossing

4.3 Vehicle to Infrastructure communication (WiMAX - IEEE802.16d-2004)

The WiMAX throughput and signal strength in the V2I scenario for LOS and NLOS environments are shown in Figure 4.8 and Figure 4.9 respectively. The results represent a representative test run that lasted for 100 seconds. The WiMAX data rate drops from around 5 Mbps to around 500 kbps as soon as the vehicle becomes mobile. We determined that the cause of this to be modulation change from 64QAM to either BPSK or QPSK caused by increased BER.

4.3.1 Vehicle on LOS route

The average vehicle speed was 31km/h and a total data transfer of 6.35 MB at an average data rate of 521 kbps with an average jitter of 8.22 ms.

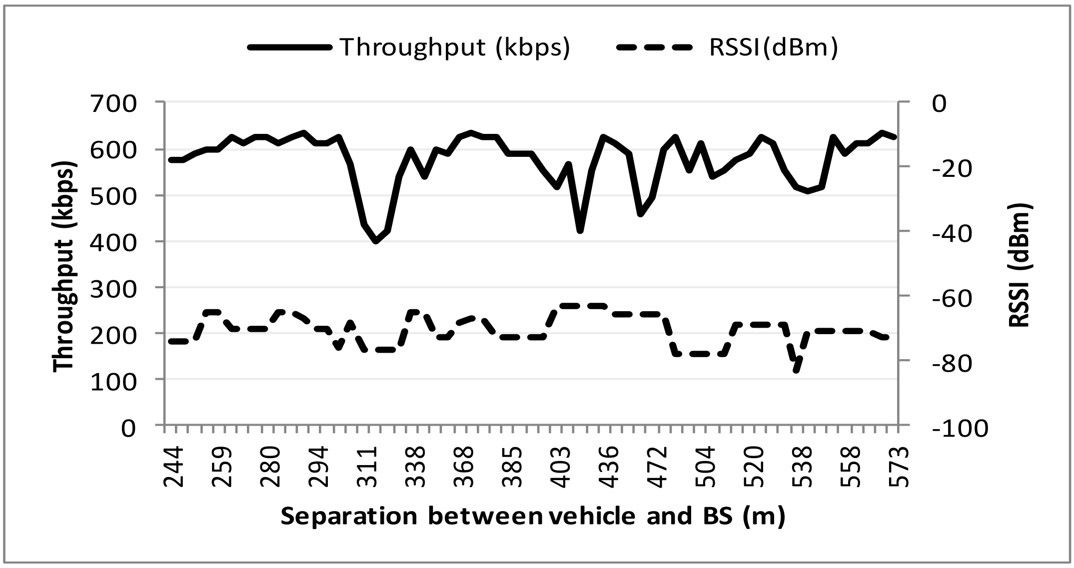


Figure 4.8. V2I communication in LOS condition

4.3.2 Vehicle on NLOS route

The average vehicle speed was 33 km/h. The average data rate of 518 kbps was reached and produced a total data transfer of 6.33 MB with an average jitter of 8.56 ms.

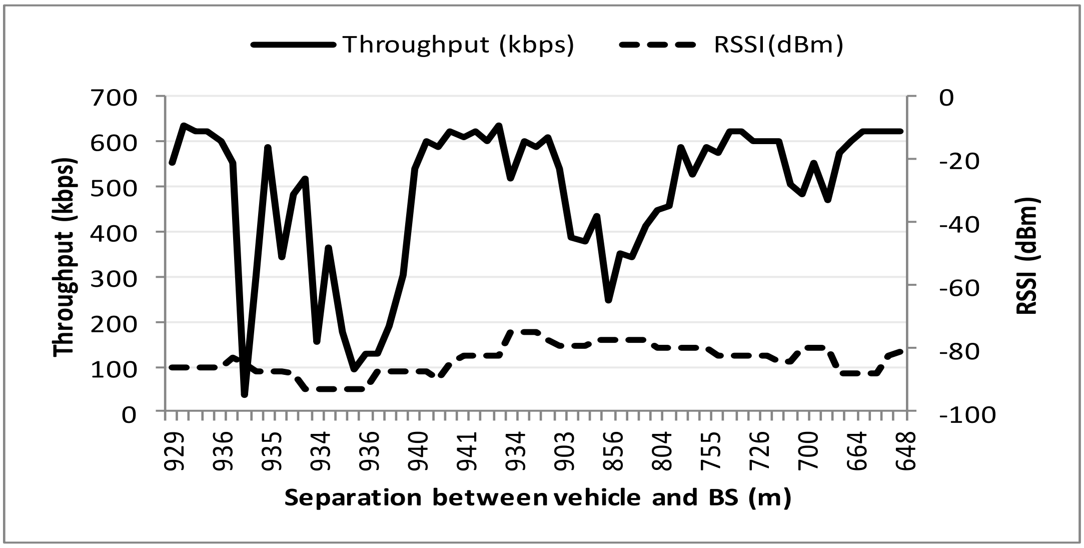


Figure 4.9. V2I communication in NLOS condition

The NLOS signal strength is weaker than that of LOS test due to the distance from the base station and the presence of obstacles that affect the signal. This can also be seen from the data rate plot: Even though the data rate peaks at about the same value as in LOS conditions, in NLOS the fluctuation is higher and the data rate drops too close to zero.

4.4 Vehicle to Vehicle to Infrastructure communication (Wi-Fi - IEEE802.11n and WiMAX -IEEE802.16d)

4.4.1 Vehicles following each other

Figure 4.10 shows the throughput and signal strength for vehicles following each other in an urban environment under LOS, and for NLOS in Figure 4.11. The average link throughput for LOS and NLOS in the V2I only tests is also shown for reference.

4.4.1.1 WiMAX vehicle on LOS route

The graph shows a noticeable increase in data rate at an intersection where the vehicles had to stop. The temporary cessation has this effect on the throughput due to the lower WiMAX BER. This event is followed by data rate decrease as the distance between the vehicles increased to 150m with respect to the second vehicle still at the intersection. But the throughput settles to the same value as that of V2I average, showing the performance dependence on WiMAX.

The average absolute vehicle speed was 27 km/h with an average vehicle separation of 31 m. This resulted in an average data rate of 539 kbps and total data transfer of 6.64 MB in the 100 seconds period.

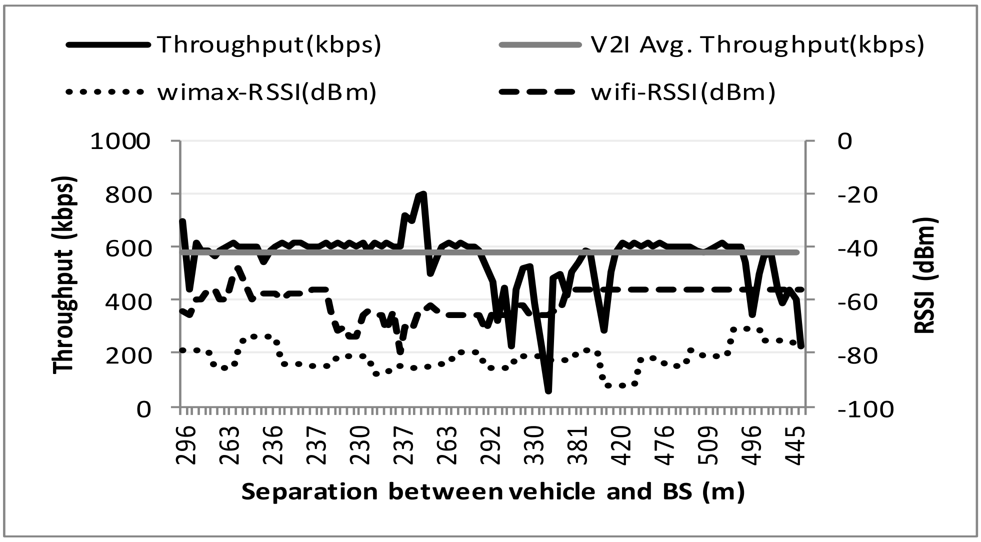


Figure 4.10. V2V2I following under LOS condition

4.4.1.2 WiMAX vehicle on NLOS route

The performance is similar to that experienced for V2I as we see similar average throughput measurements: The visible difference being the high fluctuation in data rate and signal strength. Again a data rate increase is noticeable where the vehicles stopped at an intersection.

The 100 seconds period at an average separation between the vehicles of 40 m travelling at an average speed of 25 km/h resulted in an average data rate of 543 kbps and total data transfer of 6.7 MB.

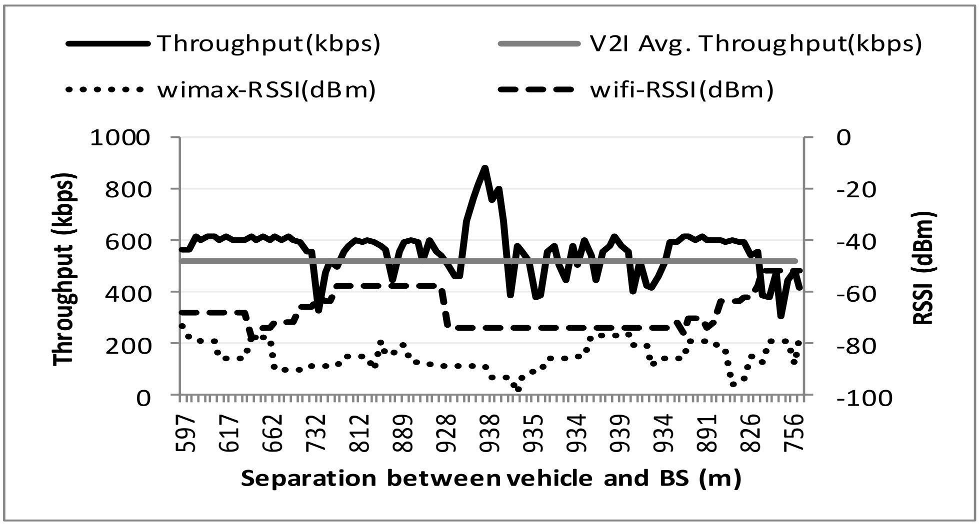


Figure 4.11. V2V2I following under NLOS condition

4.4.2 Vehicles moving in opposite directions

Throughput and signal strength for vehicles moving in opposite direction under LOS and NLOS conditions are shown in Figure 4.12 and Figure 4.13 respectively. The average throughput for LOS and NLOS V2I is also plotted for reference. The distance between the two vehicles is plotted on the x-axis whereby the vehicles cross each other at the centre of the graph.

The same behaviour of Wi-Fi RSSI as in V2V is seen here where it increases as vehicles come close to each other but the data rate does not increase with RSSI as we saw before because of the inclusion of WiMAX.

4.4.2.1 WiMAX vehicle on LOS route

In this setup an average relative vehicle speed of 58 km/h was recorded with an average distance from the base station of 441 m. The contact time of 36 s produced an average data rate of 454 kbps, jitter of 10.3 ms and total data transfer of 1.83 MB.

The data rate starts lower, but quickly stabilises as soon as the link is established between the two vehicles. The data rate peaks at the same value as in V2I when only WiMAX is used; this shows that when within Wi-Fi range, the performance depends on the WiMAX connection.

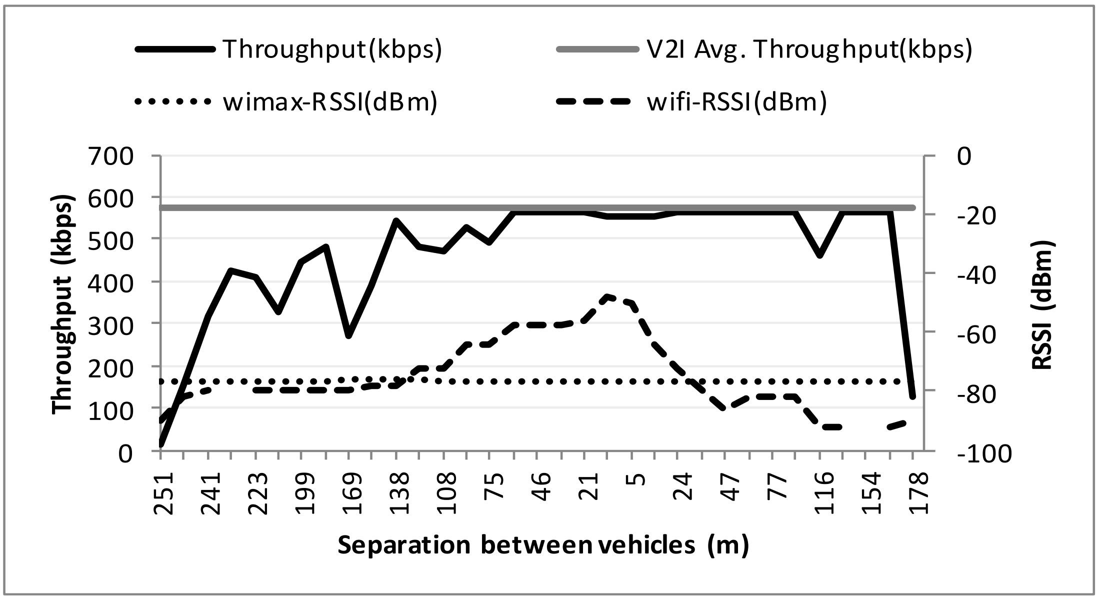


Figure 4.12. V2V2I moving in opposite direction LOS

4.4.2.2 WiMAX vehicle on NLOS route

Under NLOS the signal strength is not stable as in LOS where the communication range is short, due to the vehicle BS separation and presence of obstacles that continually affect the signal. The resulting throughput is accordingly unstable. But even under unstable conditions of signal strength the throughput on average still matches that seen in the V2I test.

The experiment was carried out under the average vehicular relative speed of 55 km/h and average maximum separation of 192 m was reached. The average contact lasted for 35s with an average data rate of 451 kbps producing total data transfer of 1.82 MB and 13.9 ms jitter.

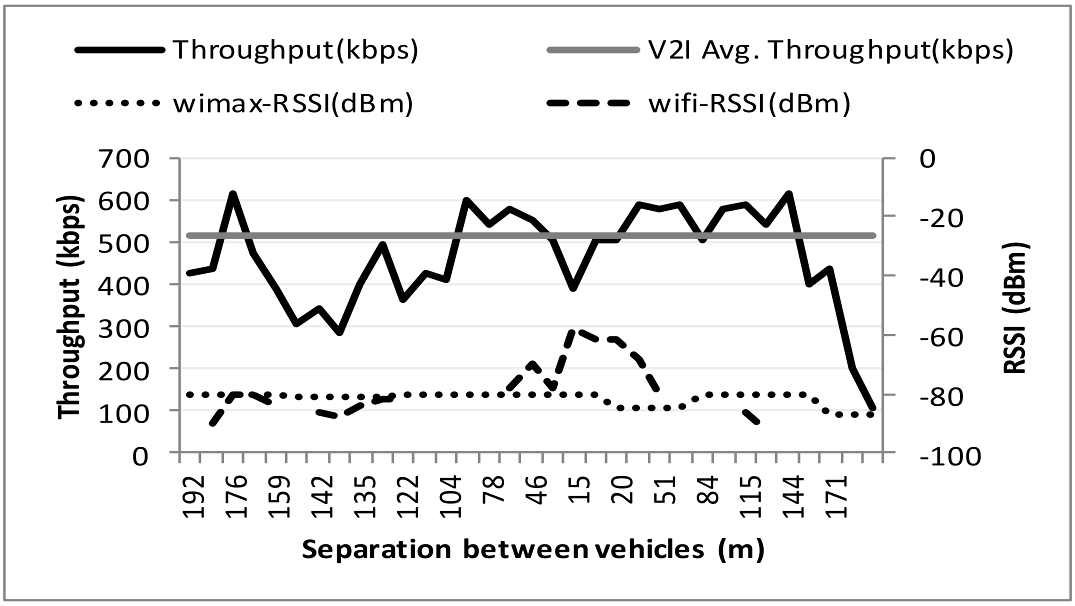


Figure 4.13. V2V2I moving in opposite direction in NLOS

4.5 Result Summary

The average values measured in all experiments performed are shown in Table 7. The results show link duration dependence on the vehicles direction and the radio range. Communication between vehicles traveling in opposite directions is very short lived when compared to communication period between vehicles traveling in the same direction. Also, the longer the radio's range, the longer the link duration. For this reason, in V2V communication where Wi-Fi was used, an increase in throughput is visible when vehicles follow each other than when moving in opposite directions. But this does not mean Wi-Fi performance is poor when vehicles are not moving in the same direction as the maximum data rate achievable in both cases is similar. Because the throughput is an average of the entire contact period, e.g. 33 seconds, the total average throughput is lower when moving at opposite directions due to the weak signal strength at the edge of communication range. The same behaviour is experienced for V2V2I even though here the difference is not much due to the low throughput limitation induced by WiMAX. We also observe that under both LOS and NLOS conditions the throughput for WiMAX is not significantly different. This is because the WiMAX CPE is built for use under NLOS conditions, and can therefore adapt to different changes in link condition caused by obstacles, reflections etc. This is done by constant monitoring of uplink and downlink to ensure selection of the best antenna(s) at any given moment [118]. The same behaviour is seen for the throughput in V2I to that in V2V2I for vehicles following and moving in opposite directions scenarios. Here the throughput stays the same as Wi-Fi has much larger data rates than WiMAX; hence the only determining factor is WiMAX.

Table 7 also gives the average jitter incurred for each test. In V2V communication where IEEE 802.11n is used, we see a lower jitter when cars are following each other than when they are moving in opposite directions. For the V2I case where only WiMAX is used we see an increased jitter compared to V2V where Wi-Fi was used. We also observe an increase when operating under NLOS conditions due to the signal being reflected and weakened by blocking buildings and other objects. We further see an increased jitter in V2V2I when both Wi-Fi and WiMAX operate together. Similar to the results reported in [3, 111, 129], vehicle speed does not seem to impact throughput and jitter but rather the contact time hence the total data transferable. Distance between the communicating vehicles on the other hand, no matter their direction of movement, impacts throughput and jitter.

Table 7. Wi-Fi and WiMAX performance in different VANET architectures

		V2V		V2I		V2V2I			
Average Values		Crossing	Following	LOS	NLOS	Crossing		Following	
						LOS	NLOS	LOS	NLOS
Jitter (ms)		1.88	0.38	8.22	8.56	10.3	13.9	10.2	12.4
Speed (km/h)[1]		64	113	31	33	58	55	27	25
Separation (m)[2]	Wi-Fi	302	34	-	-	251	192	31	40
	WiMAX	-	-	443	802	441	821	383	778
Throughput (Mbps)	Avg.	13.7	31.3	0.521	0.518	0.454	0.451	0.539	0.543
	Max.	31.7	34.5	0.62	0.62	0.551	0.598	0.781	0.861
Contact Time (s)		33	100	100	100	36	35	100	100
Data Transferred (MB)		51.7	386.3	6.35	6.33	1.83	1.82	6.64	6.70

In addition to the results above, the following was performed:

- Real time internet radio audio streaming (V2V2I and V2I) at 64 kbps,
- High quality Skype voice call in V2I and V2V2I at a data rate of 96 kbps,
- Low quality live video streaming in V2I and V2V2I at a data rate of 250 kbps,
- Low quality Skype video call in V2I and V2V2I at a data rate of 250 kbps and
- HD video streaming in V2V at a data rate of 1.2 Mbps.

4.6 Applicability of Presented Results

Applications in VANETs are either event driven, periodic or on demand where some are short lived while others are long lived [3, 65, 66]. In each case a message is either broadcast/geocast or unicast in a multi-hop or single-hop fashion. Safety applications and traffic management applications consist of short messages sent in a broadcast fashion while commercial applications are large-scale and sent in unicast fashion. The safety applications are real time while non-safety applications can be real time or delay tolerant. Because safety and convenience applications are transmitted as short messages, they can easily be supported

[1] Relative vehicle speed for crossing and absolute vehicle speed for following
[2] Maximum separation between vehicles reached for crossing and separation between cars for following or separation from base station

in V2V and V2I communications whether vehicles are crossing or following each other. On the other hand, because commercial applications are of large scale, some applications require certain data rate threshold to be maintained, examples include live video streaming. Delay tolerant applications have relaxed data rate requirements (can function at any available rate) and can operate whether connections are short lived or long lived. Table 8 below shows typical data rate requirements by some of the applications and which of the communication strategies can support them.

Table 8. VANET applications with data rate requirement

Data Rate	**Application**	**V2V**	**V2I**	**V2V2I**
1.5 Mbps	HD Video	√	-	-
500 kbps	High quality video	√	-	-
128 kbps	Low quality video	√	√	√
100 kbps	High quality voice	√	√	√
24 kbps	Low quality voice	√	√	√
10 kbps	Traffic management	√	√	√
5 kbps	Safety messages	√	√	√

From the results gathered, vehicles following each other provide higher average throughput and longer connection time resulting in large data transfers. Vehicles moving in opposite directions resulted in lower average throughput and contact period based on relative speed. Depending on the mode of communication, a certain amount of data can be transferred hence a suitable application can be implemented. Table 9 gives the possible applications that can be implemented for 30 seconds connection period at a relative speed of 60 km/h.

Table 9. Applications as per communication architecture

Application	V2V	V2I	V2V2I
Safety Messaging	√	-	-
Torrent	√	√	√
Email	√	√	√
Navigation (Map Downloads)	-	√	√
File sharing (up to 50MB)	√	-	-

Chapter 5 Conclusion

Feasibility of infotainment applications in vehicular ad hoc networks depends not only on vehicular network characteristics but as well as the communication medium in terms of its performance under such networks. In this research, the performance of Wi-Fi as a provider of inter-vehicular communications and WiMAX for vehicle to infrastructure communications in a simple vehicular ad hoc network was evaluated. Experiments in scenarios with representative vehicle speeds, levels of urbanisation, contact ranges and contact durations were conducted.

Wi-Fi, used for the V2R and V2V connection, was found to provide reliable and high throughput, while connected. The Wi-Fi connection was unaffected by speed and the only distinguishable factor seems to be separation which determined whether the connection is made. The use of external antenna proved to increase the performance in terms of communication ranges and link duration. Ranges of up to 300 meters were achieved with external antenna while only 150 m was reachable with normal laptop antenna.

WiMAX throughput, used for V2I communications, is severely affected by even slight mobility. This is due to the 802.16d (2004) designed for fixed wireless communication and not mobile communication. Once mobility is introduced error rate increases therefore forcing the use of less aggressive modulation techniques. The WiMAX throughput is predictable and stable for the vehicular speeds tested, but mobile throughput is a fraction of the stationary throughput. The WiMAX throughput fluctuates for NLOS, but this does significantly not affect the average throughput.

Applications that require high data rates, e.g. HD video transfer and large file sharing, can easily be hosted on V2V communication because of higher Wi-Fi data rate support. The V2I and V2V2I interface can support applications that require low data rates. The setup is particularly well suited for delay tolerant applications. Streaming video, streaming audio and video conferencing was successfully run in the V2V2I setup.

Chapter 6 Future Work

The results in this research present the best case scenario in vehicular networks where only two nodes communicate where there are no collusions and contentions with other users. It would be beneficial to know the performance where more than two nodes try to communicate. Therefore further investigations would be performed under denser scenarios where a number of vehicles share single medium. This will also include the employment of multi-hop communications. Additionally the use of mobile WiMAX and the IEEE 802.11p will be experimented to realise more realistic communications behaviours in VANETs.

The existence of different multiple wireless communication technologies in VANETs would certainly require a way of managing them, i.e. a mechanism that decides which wireless technology to use. This mechanism on the other hand should allow for availability of safety applications' channels at all times irrespective of the technology currently selected for use. Thus, further research would be undertaken to investigate the implications of using multiple wireless technologies and management of their coexistence.

Knowing the performance of the individual communication technologies and their coexistence, the next step involves enabling content or data sharing. Because communication links are short lived in VANET's, content downloading and or uploading can only be done in blocks. Thus, content data retrieval and indexing, needs a special attention; therefore an issue that would be investigated in the coming research. Another important issue is the addressing for Internet access in vehicular networks. Nodes in VANET's are highly mobile thus the potential to continually change Internet gateway thus ISPs.

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